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Title:	NMSU CHME 491 - Introduction to Nuclear Criticality Safety Weeks 1-4 Course Material
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NMSU CHME 491 – Introduction to Nuclear Criticality Safety

Weeks 1-4 Course Material

Week 1 – Course Overview

Introductions to the course, syllabus, and the profession

Overview

- Introduction to Nuclear Criticality Safety
- Meet your instructors
- Canvas tour
- How to succeed in this course
- Reading & assignments
- Extra resources

Nuclear Criticality Safety

What is it?

- Protection against the consequences of a criticality accident, preferably by prevention of the accident

Why is it important?

- Safety is a value
- Required by DOE and LANL policy
- Accounts for 3 of 32 post Manhattan Project Fatalities
  - 3 of 20 non transportation related fatalities

What is a Criticality Accident?

- The release of energy as a result of accidentally producing a self-sustaining or divergent fission chain reaction
- You CANNOT MITIGATE a criticality accident, only prevent it

Uncontrolled and Unshielded

Meet Your Instructors

Alicia Salazar

Super Cool Criticality Safety Analyst, LANL

- NMSU CHME Alumna, B.S. 2012; University of Michigan, M.S. 2014 in Nuclear Engineering
- Worked full time at LANL for 3 years; was a student intern for ~4 years before that
- I enjoy reading, hanging out with my cats and family, and playing golf whenever I get the chance

Andrew Wysong

Nuclear Criticality Safety Division Leader, LANL

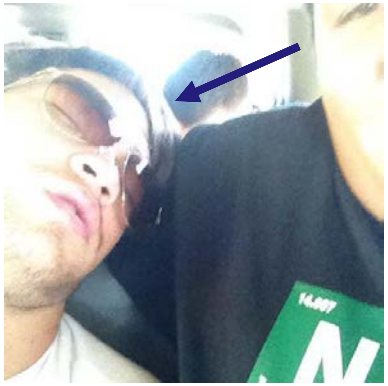
- UC Berkeley Alumnus, B.S. in NE, ME; M.S. 2009 in Nuclear Engineering
- LANL division Leader since 2015, employee since 2014
- Criticality Safety Manager at Lawrence Livermore National Laboratory 2012 – 2014
- Criticality Safety Engineer at Atomic Weapons Establishment, 2012

Meet your On-Campus TA

Elijah Wade

Nuclear
Criticality Safety
Grad Intern

eliwade@nmsu.edu



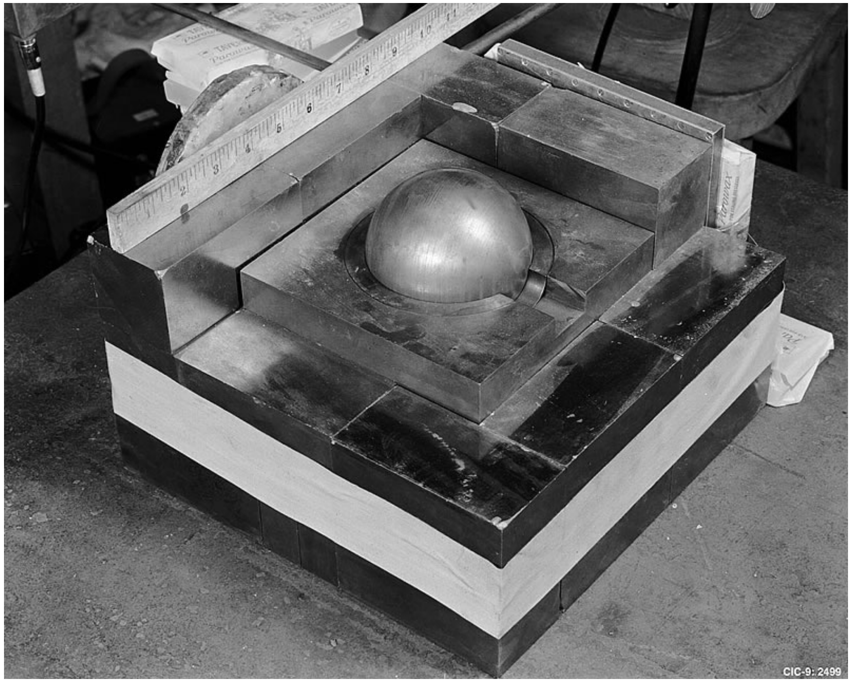
- NMSU CHME MS Student
- President of ChEGSO for 2017-2018 school year
- Interned at LANL over the summer and helped create the course
- I enjoy other people's suffering, sleeping, and taking photos of people who fall asleep in public

- Ask Elijah for help if you need:
  - Clarification on a subject
  - Help understanding the material
  - Help figuring out how the conference call on Canvas works
  - A friend
- Send an e-mail to meet with him. Office hours will be posted later
- Don't worry about interrupting him. He has no life, he's a grad student.

Introduction to Nuclear Criticality Safety

A nuclear criticality accident occurs when a fissionable material becomes “critical,” meaning that the material can sustain itself in a chain reaction, releases harmful radiation to its surroundings. Without proper shielding, nearby workers can receive a harmful or lethal dose of radiation.

Criticality safety analysts identify possible upset conditions and parameters to define boundaries and specifications for the process. These boundaries are used to reduce the risks and chance of exposure to a relatively safe level.



The “Demon Core,” having an unfavorable geometry, being encased in neutron-reflecting tungsten carbide. More information in Chapter 3.

Why nuclear criticality safety?

Nuclear criticality safety is about getting people back home safely every day. A criticality accident can occur at any stage during the processing of fissile materials, and the controls that criticality safety analysts suggest and implement are directly responsible for keeping our neighbors and coworkers safe.

I get to come to work each day and go home knowing I helped keep somebody safe today, and they get to go home to their families at the end of the day in part because of the work I did to support them.

With only ~300 practicing criticality safety engineers across the country, job security is excellent and demand is high. With many analysts retiring, there is a vacuum to fill in nuclear criticality safety divisions in the United States.

How to succeed in this course

- **Follow the directions in the syllabus, discussions, and assignments**
- Have some physical space for the class – keep the book and any printed papers with your other textbooks.
- Create your own schedule to follow each week for studying for the class
- Spread the work over several days
- Use the study sheets to review the material
- Use your online community to make friends or ask questions if you get stuck
- Don’t be afraid to ask instructors for help – Crit safety is not intuitive!

Week 1 Reading and assignments

- Read the Syllabus
- Read Knief, Ch. 1 (2 pages), No study sheet this week
- Fill out the doodle for bi-weekly class meetings
- Take syllabus quiz
- Do the Week 1 Discussion and peer review

Due Dates:

Syllabus quiz	Sunday, 11:59 PM
Discussion	Friday, 11:59 PM
Disc. Peer Review	Sunday, 11:59 PM

Resources:

- [5 tips to succeed in an online course]

Week 2 – Nuclear Physics

A crash course in Nuclear Science and Engineering

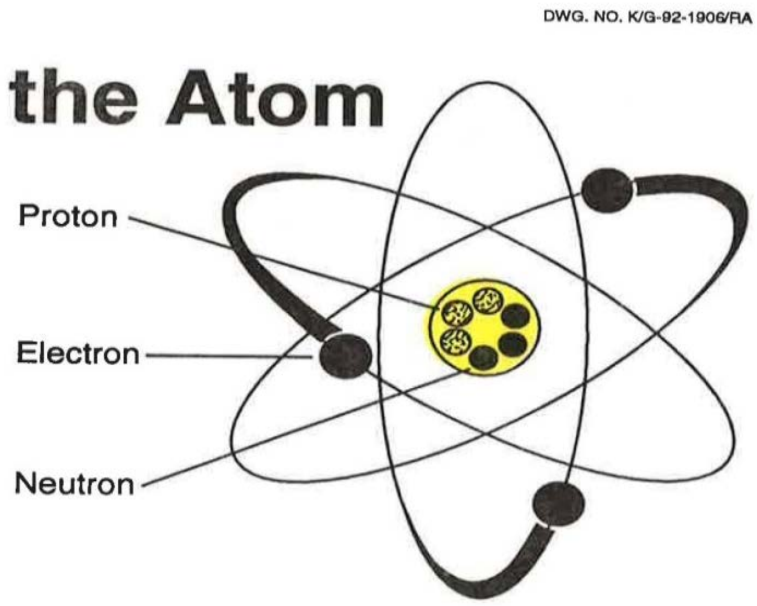
Learning objectives

After this week, you will be able to:

1. **Define the following terms**
   - Excitation energy
   - Cross section
   - Fissile material
   - Fissionable material
   - Fertile material
2. **Define nuclear reactivity and describe how it is measured**
3. **Discuss fissile, fissionable, and fertile material and their differences**
4. **Explain why only the heaviest radioactive nuclear atoms are easily fissioned**
5. **Sketch the fission cross section for both U-235 and Pu-239 as a function of neutron energy. Label each significant energy region and explain the implications of the shape of the curves for criticality safety.**

Structure of the Atom

- Molecules are collections of atoms in a chemical bond (like H_2O)
  – **Atom:** The smallest particle of an element that cannot be divided or broken up by chemical means.
  – **Proton:** An elementary nuclear particle with a positive electric charge located in the nucleus of an atom.
  – **Neutron:** An uncharged elementary particle with a mass slightly greater than that of a proton, and found in the nucleus of every atom heavier than hydrogen*.
  – **Electron:** An elementary particle with a unit negative charge and a mass 1/1837 that of the proton. They surround the positively charged nucleus and determine the chemical properties of the atom.



The nucleus (central core) of an atom consists of protons and neutrons. Electrons revolve in orbits in the region surrounding the nucleus.

Atomic Nomenclature

Atoms and isotopes are explained using the nomenclature shown on the right.

$$ {}^{A}_{Z}X $$

Where:

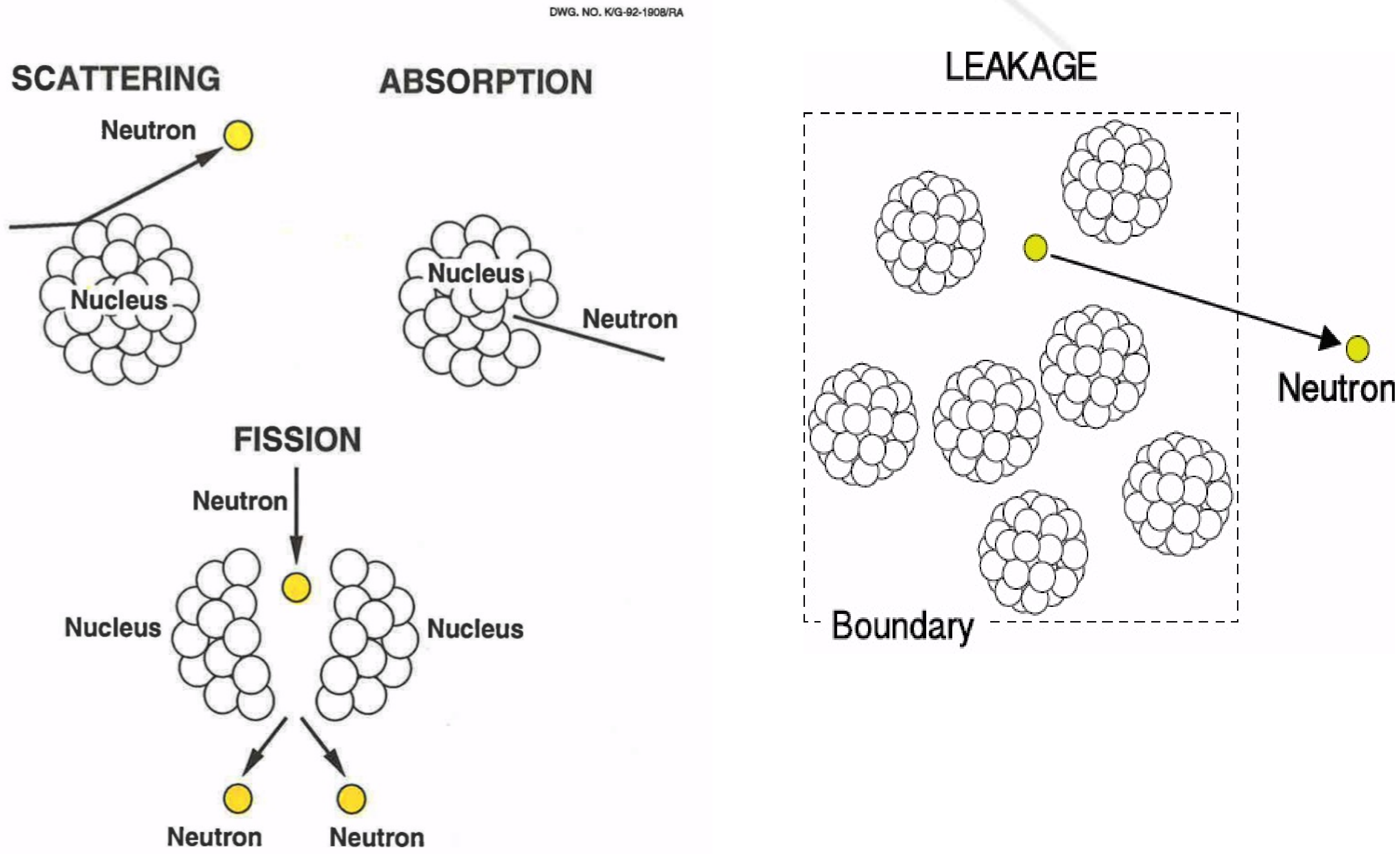
- **X is the chemical symbol**
- **A is the mass number**
- **Z is the number of protons, also known as the atomic number**
- **N is the number of neutrons**

$$ A \equiv Z + N $$

Z is often omitted since showing Z and X is redundant. All X have the same Z (${}^{235}_{92}U$, ${}^{238}_{92}U$, etc.)

Nuclei with varying A but same Z are isotopes of each other. For example, ${}^{235}_{92}U$ and ${}^{238}_{92}U$ are isotopes of U.

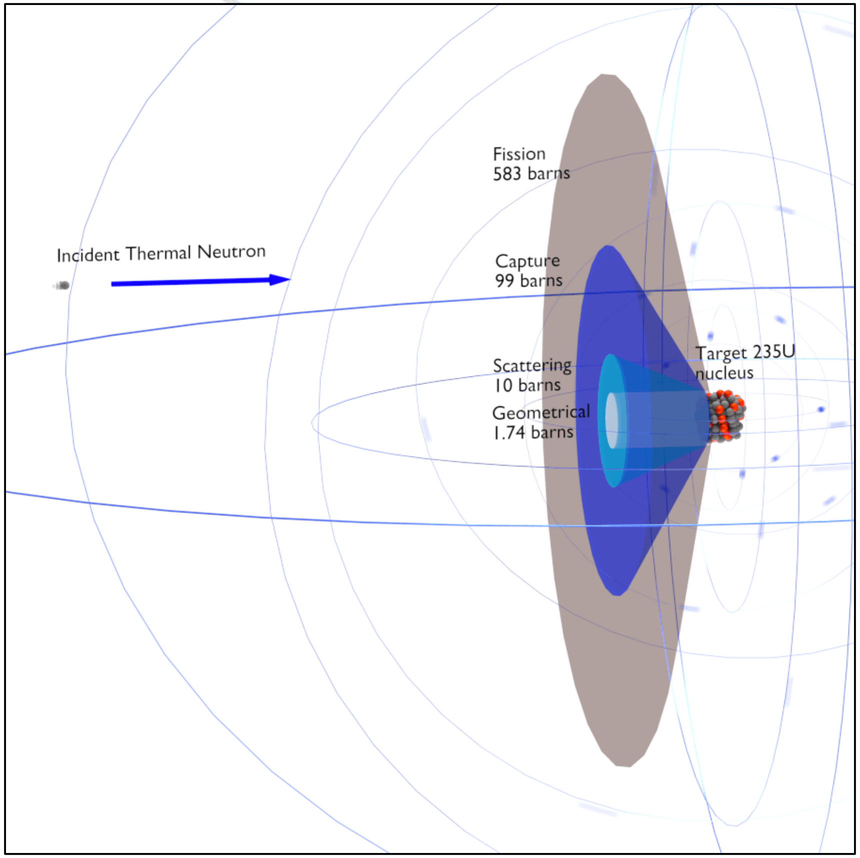
Different Neutron Interactions with an Atom



Interaction Cross-Sections

- Microscopic: effective cross section for a single nucleus of the target ‘seen’ from the incident neutron.
  - Units in barns (10^{-24} cm^2)
- Macroscopic: probability per unit length of a neutron interacting through a material

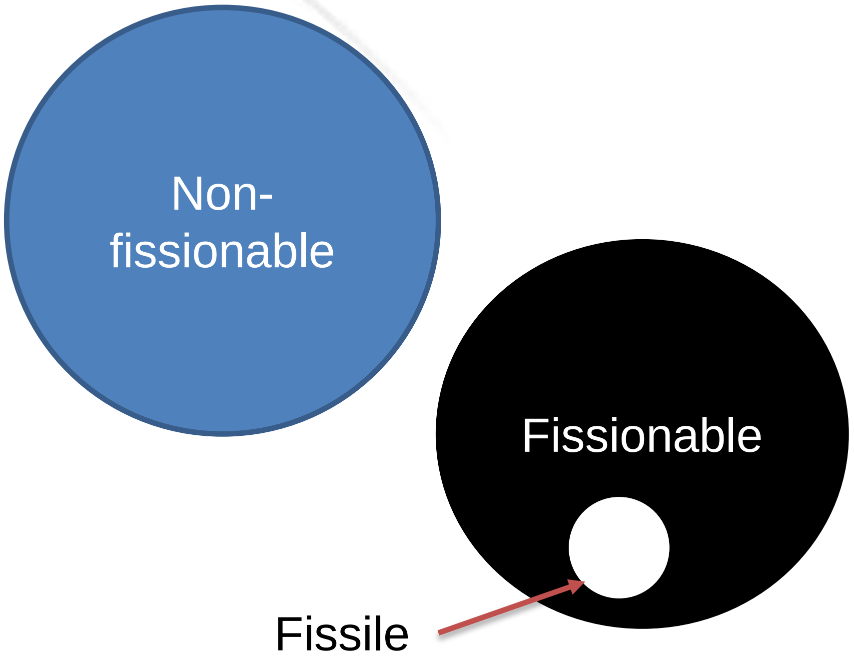
Fun fact: barn was a secret unit developed by LANL that came from the idiom, “Couldn’t hit the broad side of a barn,” since a barn unit was considered a very large target to hit with a neutron.



Example of a microscopic cross-section of ^{235}U. Image retrieved from http://www.nuclear-power.net/neutron-cross-section/

Fissile, Fertile, and Fissionable

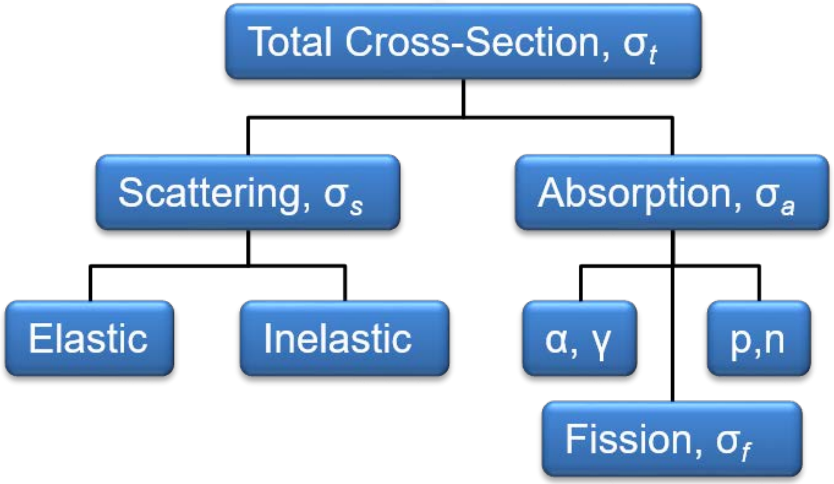
- Nuclear material can be classified in the following categories:
  - Fissionable material: Any nuclide capable in undergoing fission with fast (1-20 MeV) or thermal (~0.025 eV) neutrons
  - Fissile material: Any nuclide capable of undergoing fission after absorbing thermal (low-energy) neutrons
  - Fertile material: A non-fissile material that can be converted to fissile material through neutron capture



All fissile material is fissionable, but not vice versa. Fertile materials are non-fissile until converted.

Cross-Section Types

- Cross-sections vary by
  - Type of beam or reaction
  - Speed or energy of the projectile
- For Criticality safety, we will focus on the fission cross-section, σ_f



Types of nuclear reaction cross-sections. Note that absorption cross-sections contain data for many more possible reactions.

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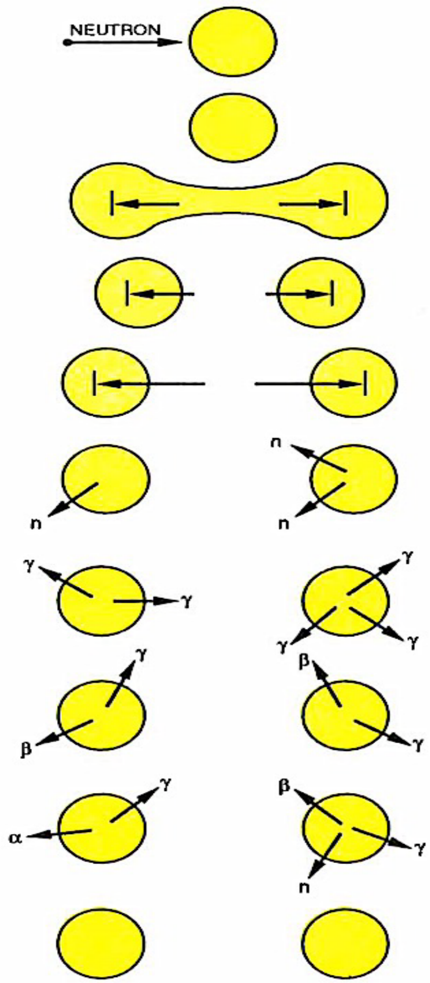
Overview of Fission Process



1) Neutron hits fissionable nucleus.
2) Nucleus absorbs neutron.
3) Neutron excites nucleus.
4) Nucleus splits into two unequal mass fragments.
5) Separation completes.
6) Fragments are excited and emit fast neutrons.
7) Each fragment emits gamma radiation (prompt).
8) α, β, γ decay process continues.
9) It may take seconds or many years to obtain stable nuclei.

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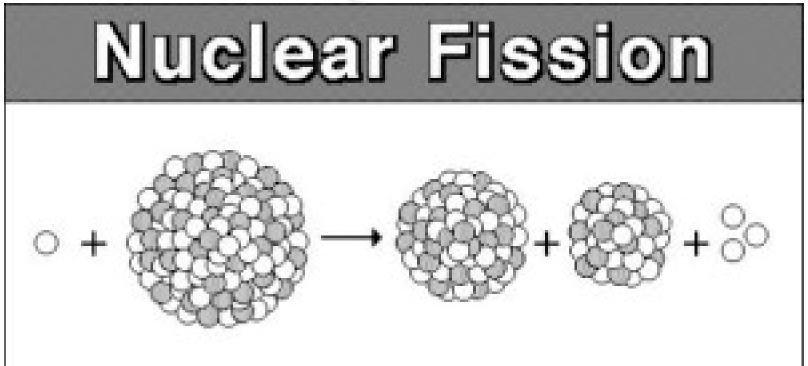
Fission Reactions

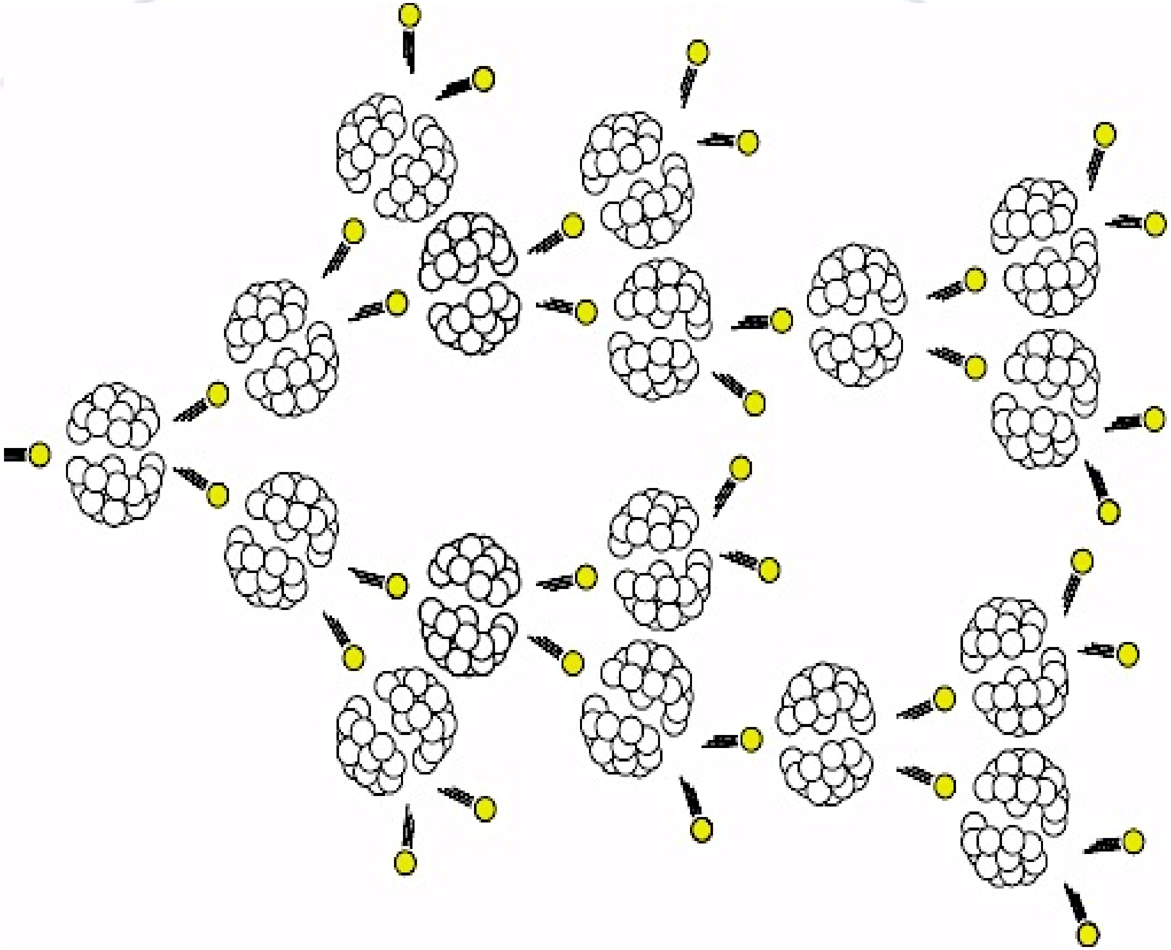
- Releases energy by splitting heavy nuclei into two lighter nuclei
- To produce a fission, the incoming neutron must add more than the excitation energy, E*, for the nucleus to reach an excited state.
- Fissions release prompt neutrons (released almost instantaneously from the fission) and delayed neutrons (released later in the process from fission fragments)



$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\,{}_{0}^{1}n + \text{Energy} $$

Example of nuclear fission reaction. Image retrieved from http://physicsfacts.com/2013/04/nuclear-power/

Neutron Fission Chain Reaction



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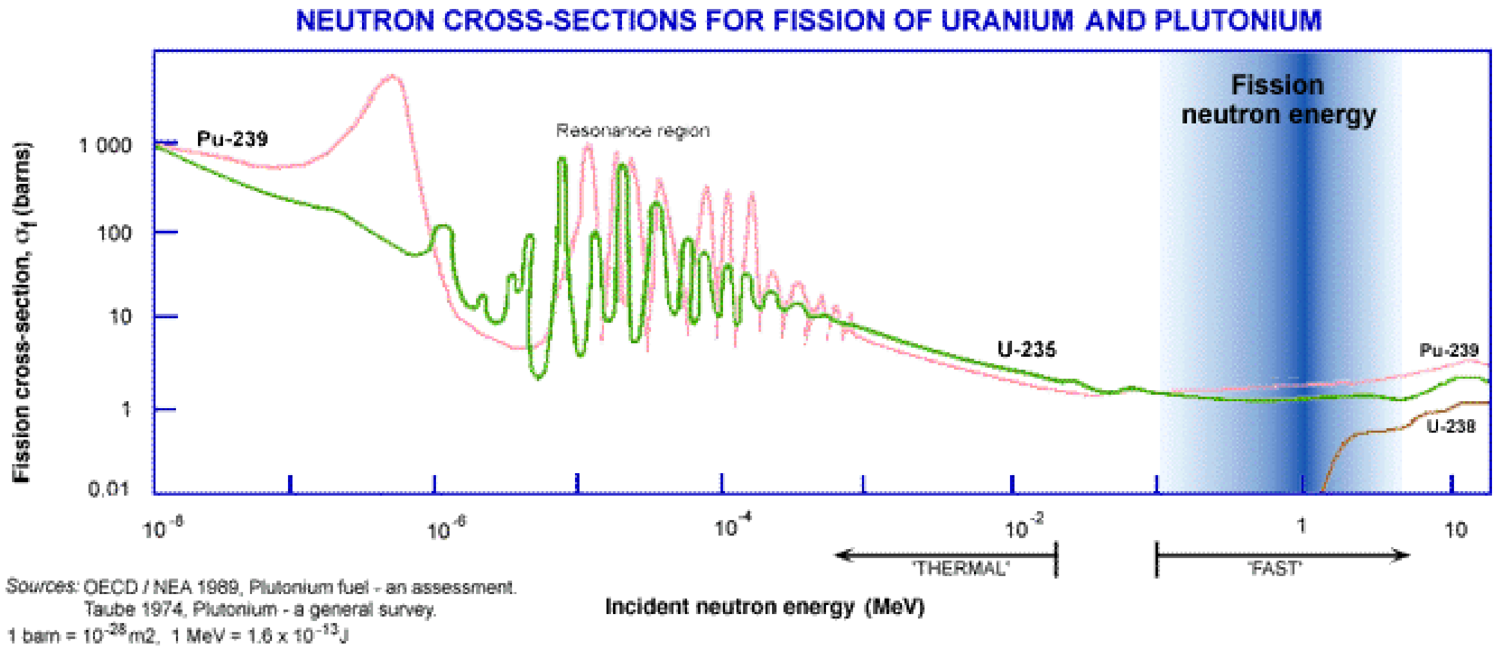
Fission Cross-Section Plots



Cross-section plots like the one above allow us to view the cross-section at different neutron incident energies (speeds). Each nuclide has its own signature curve, showing the probabilities of fission at different energy levels.

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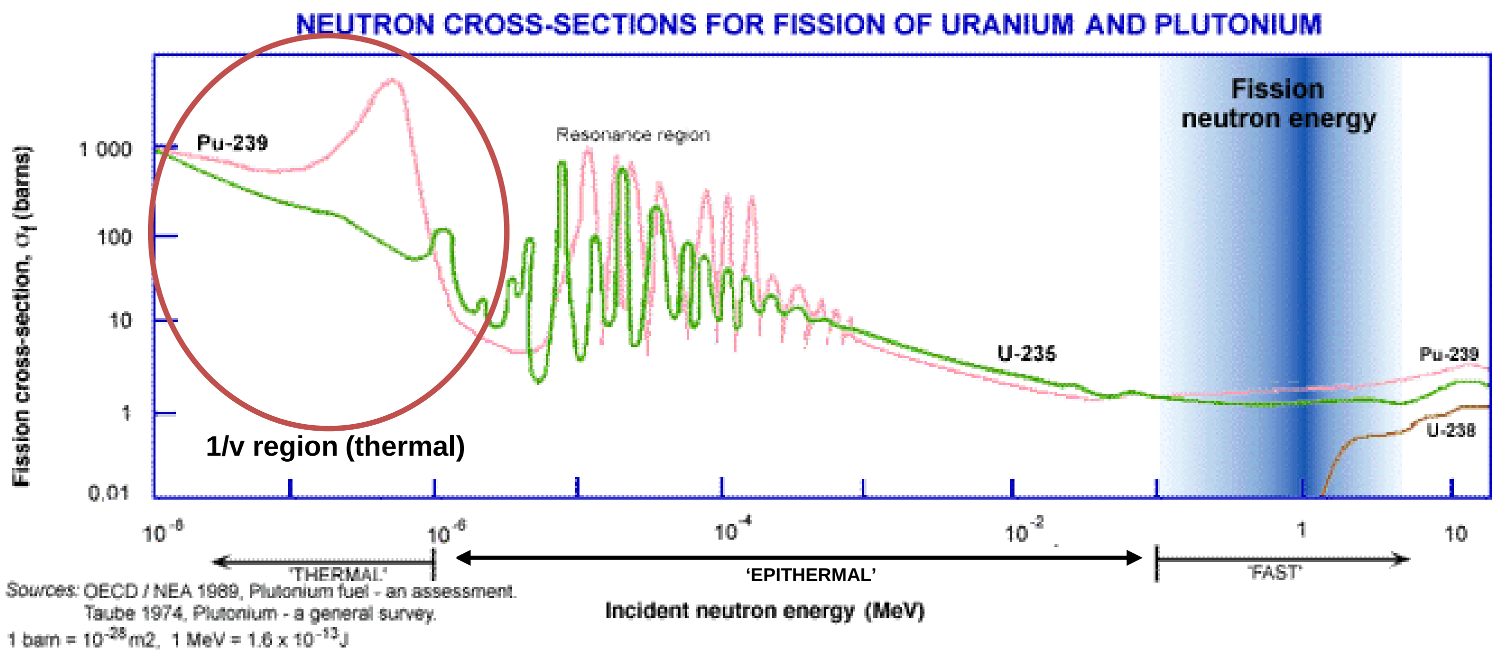
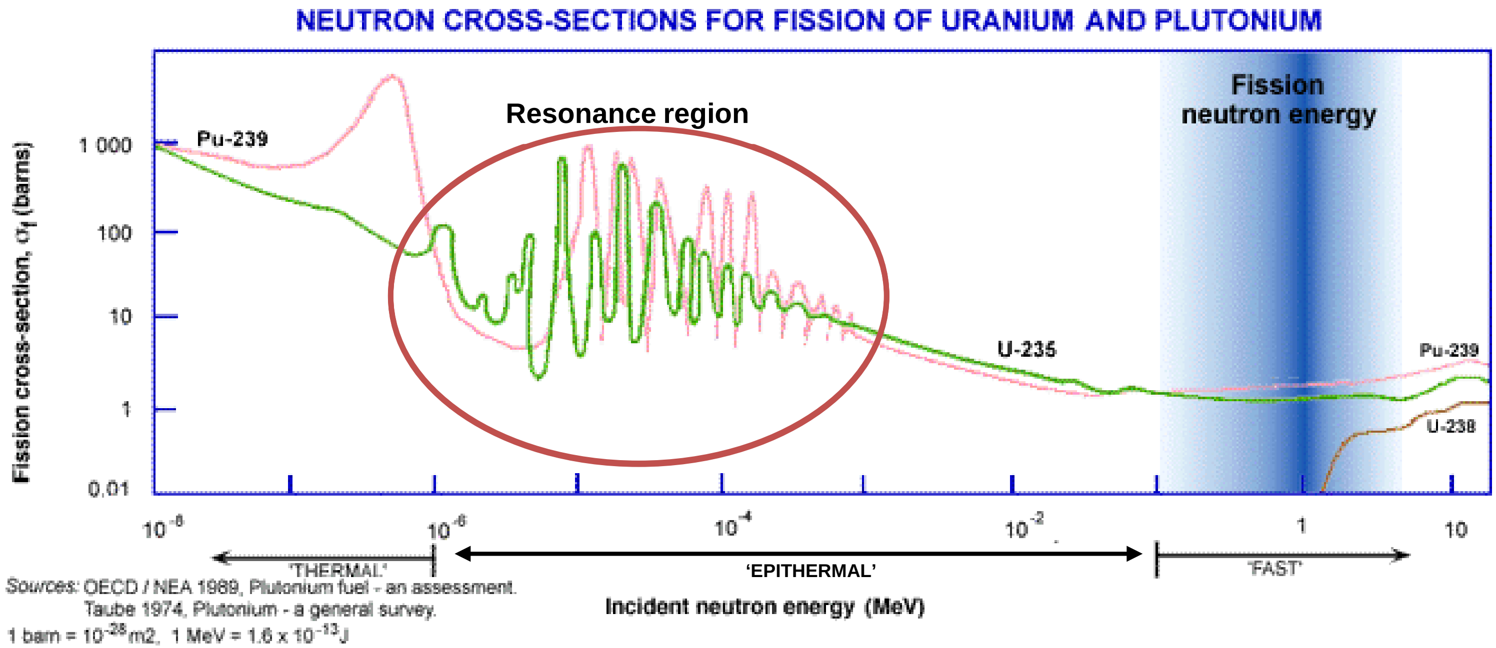
Fission Cross-Section Plots



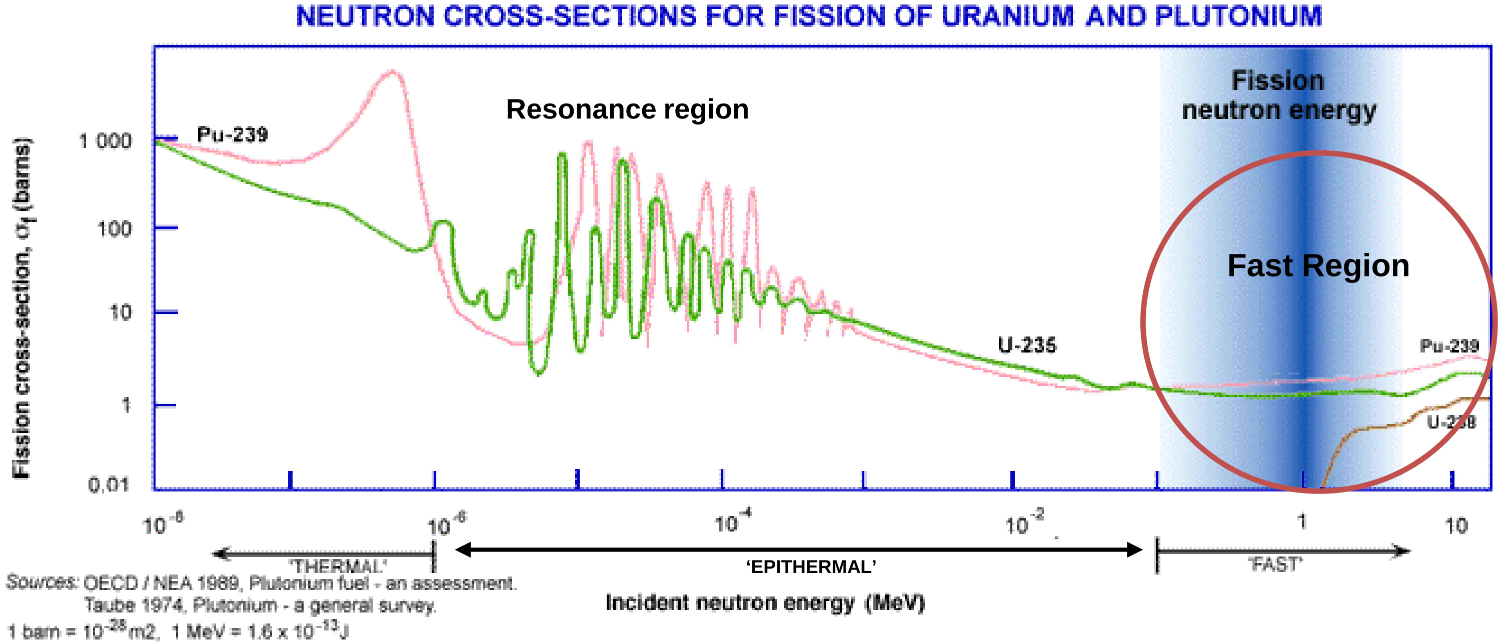
In the 1/v region,cross-section peaks can be seen for fissile materials like ^{239}Pu or ^{235}U, but not for other fissionable material like ^{238}U. This is the region that thermal neutrons interact with the target material.

Understanding the Data



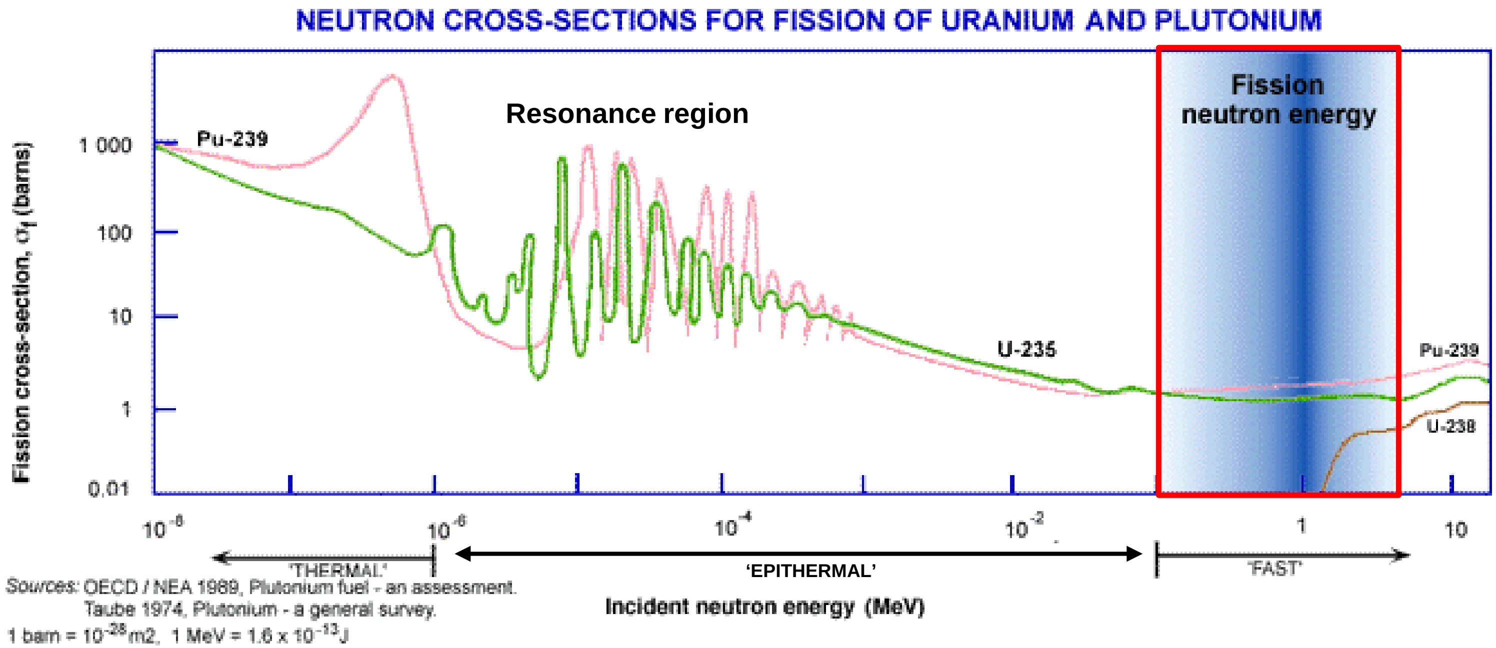
The resonance region is where the neutron and target nucleus become indistinguishable, called a compound nucleus. Each peak in the resonance region represents a particular compound state.

Understanding the Data



In the fast neutron region, neutrons carry more energy and travel much faster. Because of this, fast neutrons can apply enough energy to fissionable nuclei like ^{238}U to cause them to fission. However, fast neutrons have a lower cross-section due to their high energy, decreasing the probability of neutron capture.

Understanding the Data



If you hadn't noticed, the fission neutron energy band indicates the common ejection energy that neutrons carry when ejected from a fission reaction.

Week 2 Reading and Assignments

- Open or print the week two study sheet (found in Study Sheets folder)
- Study the slides
- Read Shultis & Faw
  - Sections outlined in study sheet
- Take the weekly quiz
- Do the discussion/peer review

Due Dates:

Syllabus quiz	Sunday, 11:59 PM
Discussion	Friday, 11:59 PM
Disc. Peer Review	Sunday, 11:59 PM

Tables to bookmark or print:

- **Shultis & Faw,**
  - Tables 1.1-1.5, units/conversions
  - Table 1.7, Avogadro's constant
  - Figure 4.1, Binding Energy/A chart
  - Table 5.1, Radioactive decay chart
  - Table 6.2: Nuclides which spontaneously fission

Supplemental Resources

- Nuclear Physics Crash Course (Youtube)
- MIT Open Courseware slides on nuclear engineering
- US Nuclear Regulatory Commission Glossary (definitions)
- Shultis & Faw, 6.5 : Reactions involving neutrons
- Shultis & Faw, 6.6 : Characteristics of the fission reaction
- LA-11627: Glossary of Nuclear Criticality Safety Terms
  - Found in 'Supplementary Reading' folder

Week 3 – Nuclear Criticality Fundamentals

Connecting Nuclear Physics and Nuclear Criticality Safety

Learning Objectives

After this week, you will be able to:

1. Define sub-critical, critical, super-critical, nu, and beta.
2. Explain the effects of the following factors relevant to criticality safety of operations: Mass, Interaction, Geometry, Moderation, Reflection, Concentration, Volume, Neutron absorbers and Enrichment.
3. Describe the interactions of the following with matter: Alpha particle, Beta particle, Positron, and Neutron.
4. Describe the use of neutron poisons.
5. Explain the absorption characteristics of the following elements in terms of their cross-sections: cadmium, boron, chlorine, gadolinium, and hydrogen.

Definition of Criticality

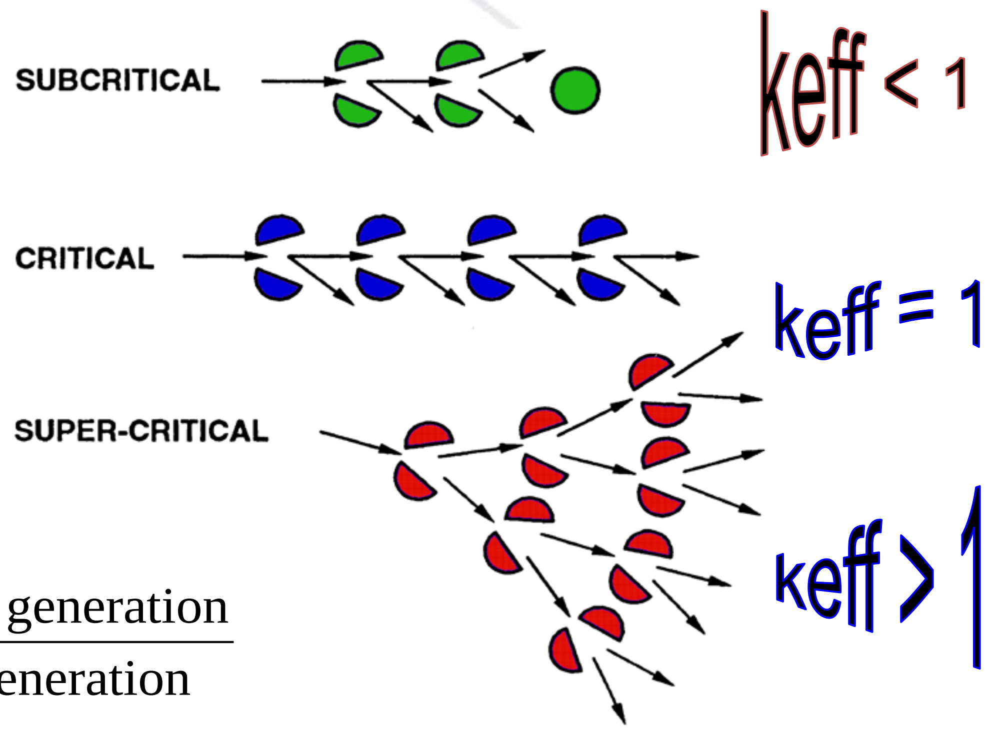
If the number of fissions occurring per second:

- Are Decreasing: the system is ***subcritical***
- Are Constant: the system is ***critical***
- Are Increasing: the system is ***supercritical***

Neutron Multiplication Factor, k_{eff}

- k_{eff} is a value used to describe the fission balance of a system
  - It is a global system property
  - It sums up the battle between leakage and absorption

How k_{eff} and Criticality are Related



$$k_{eff} = \frac{\text{neutron population in current generation}}{\text{neutron population in last generation}}$$

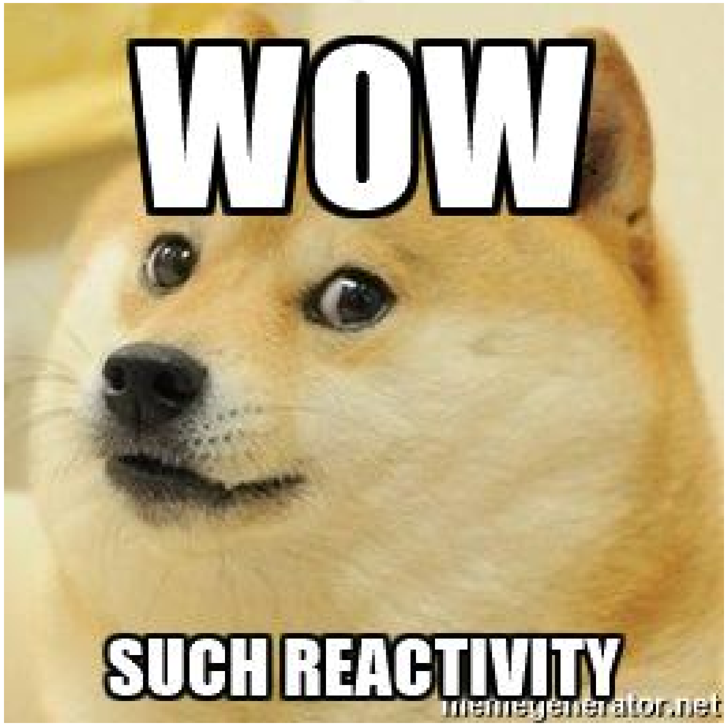
Or

$$k_{eff} = \frac{\text{Production Rate}}{\text{Absorption Rate} + \text{Leakage Rate}}$$

Reactivity, ρ

- Reactivity is the change in k_{eff}, which gives a time dimension to k. With this, we can see how violent or supercritical the reaction might get.
- Reactivity units are in $

$$\rho = \frac{k-1}{k} = \frac{\Delta k}{k}$$



Nu (ν) and Beta (β)

- $\bar{\nu} = \frac{average\ \#\ of\ neutrons\ released}{fission}$
  $= \bar{\nu}_{prompt} + \bar{\nu}_{delayed}$
  - Different for each nuclide
- $\beta = \bar{\nu}_d / \bar{\nu}$
  - delayed neutron fraction
- Both values can be found in tables and are well-defined

Nuclide	Fast Fission		Thermal Fission	
	$\bar{\nu}$	β	$\bar{\nu}$	β
^{235}U	2.57	0.0064	2.43	0.0065
^{233}U	2.62	0.0026	2.48	0.0026
^{239}Pu	3.09	0.0020	2.87	0.0021
^{241}Pu	–	–	3.14	0.0049
^{238}U	2.79	0.0148	–	–
^{232}Th	2.44	0.0203	–	–
^{240}Pu	3.3	0.0026	–	–

$\bar{\nu}$ and β table from Keepin, G.R., 1965.

Buckling, B^2

- Two types of buckling:
  - Material, B_m^2
    - Describes fissile material characteristics in infinite medium
    - $B_m^2 = \frac{\nu\Sigma_f - \Sigma_a}{D}$ where D is the diffusion coefficient
    - Measures neutron production minus absorption
  - Geometrical, B_g^2
    - Describes the geometrical characteristics of a material
    - Measures neutron leakage in a system
    - Equations vary for each geometry (obviously)
    - Affected mainly by concavity of material

For more detailed information, you can visit nuclear-power.net

Feedback From a Reaction

Positive Feedback

- Any product of the reaction that enhances the reactivity, such as:
  - Temperature and power increase, which increases reactivity

Negative Feedback

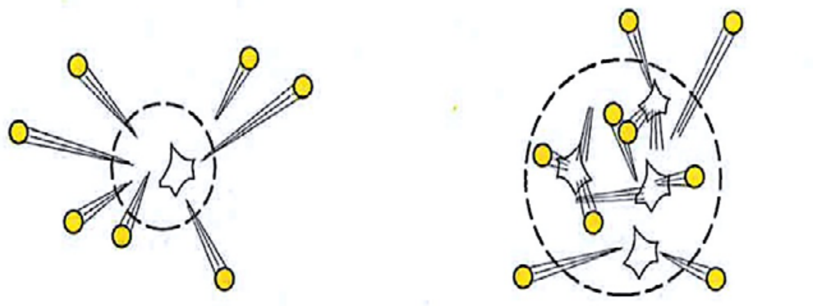
- Any product of the reaction that controls the reactivity, such as:
  - Boiling, in cases of undermoderation where the criticality becomes stable with less water.

Parameters of Importance

- Parameters that affect k_{eff} are:
  - **M**ass
  - **A**bsorption
  - **G**eometry/Shape
  - **I**nteraction
  - **C**oncentration/Density
  - **M**oderation
  - **E**nrichment
  - **R**eflection
  - **V**olume
- Parameters are somewhat interdependent
  - Changing one often changes others

Mass

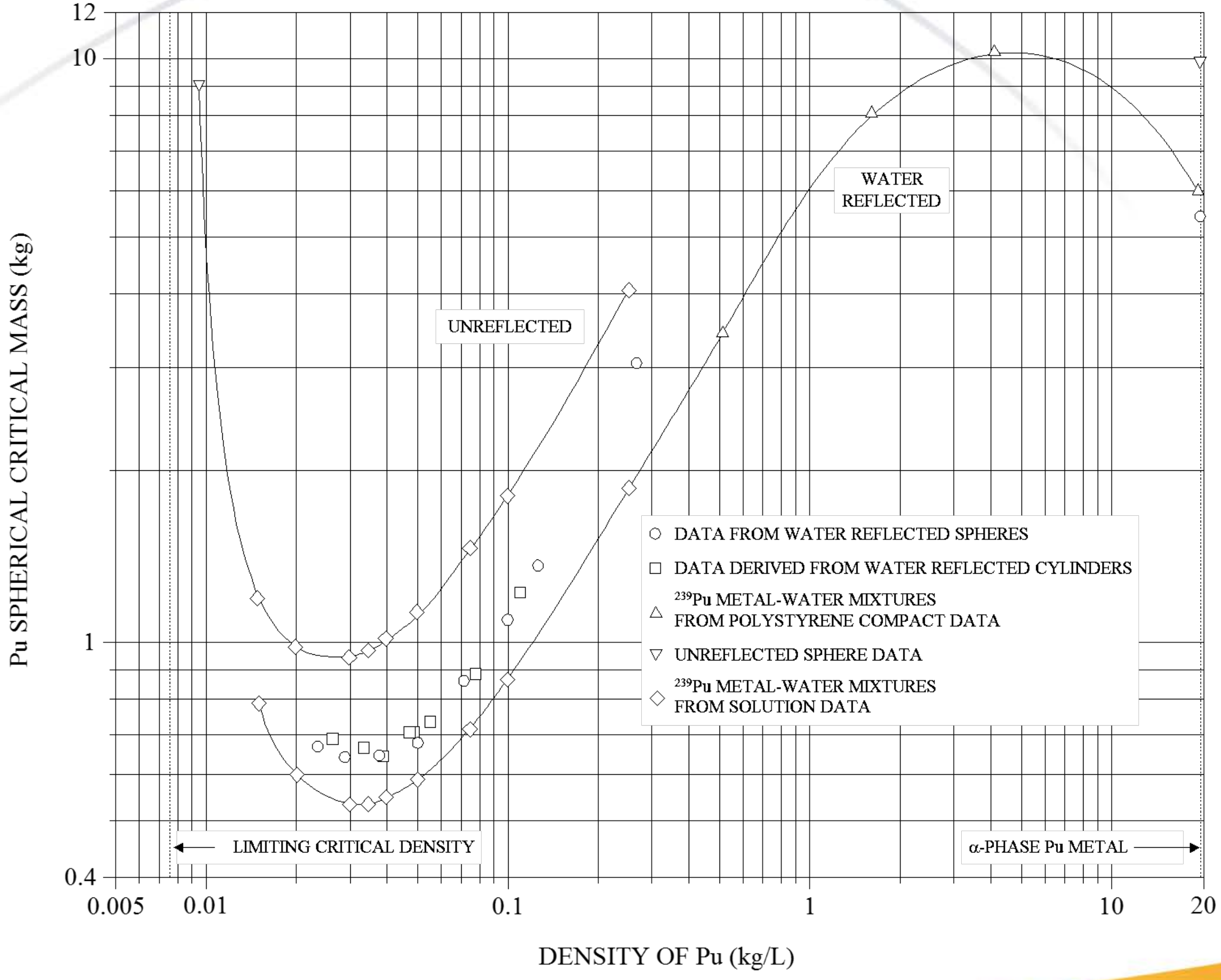
- Fissionable materials have a critical mass, the amount of material required to support a fission chain reaction
  - Varies for different materials and forms (i.e. metal, oxide, solution, etc.)
- Mass is controlled by limiting the amount of fissionable material used



Small amount of material – Neutrons escape rapidly.

Large amount of material – Fewer neutrons escape.

Pu239 Critical Mass Curve



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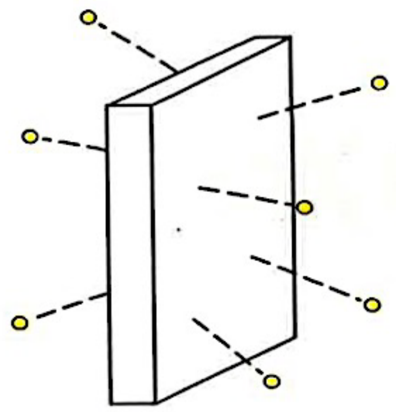
Absorption

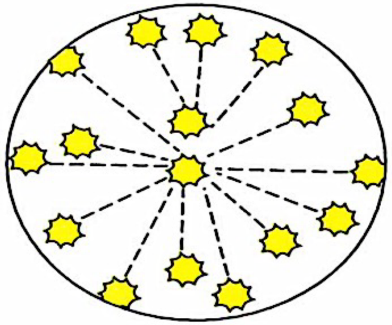
- Absorbers/neutron poisons are materials effective at capturing thermal neutrons
  - Cadmium, chlorine, and boron are good absorbers
- The absorption of neutrons which might have otherwise struck a fissionable nucleus makes the system safer
- Absorbers are not used as a control
  - Requires periodic monitoring to ensure effectiveness and presence

Geometry/Shape

- Size and shape of material are designed to be geometrically favorable
  - A large ratio of surface area to volume increases neutron leakage
- A sphere is the least favorable criticality safety geometry
  - Surface area is small for its volume
  - Neutron will likely cause more fissions before escaping



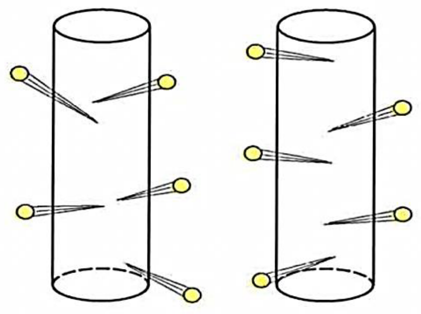
Neutrons "leak out" and do not cause fissions.



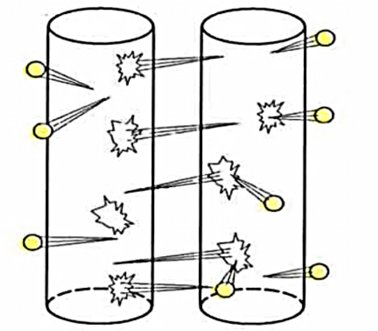
Neutrons causing fissions

Interaction

- Interaction occurs when neutrons from one location can reach and enter material at another location.
- Two or more subcritical units brought closer may become critical due to the gain in neutrons
- NCS requires 12 inches of spacing between operations
  - Operations cannot be removed without prior approval (configuration management)



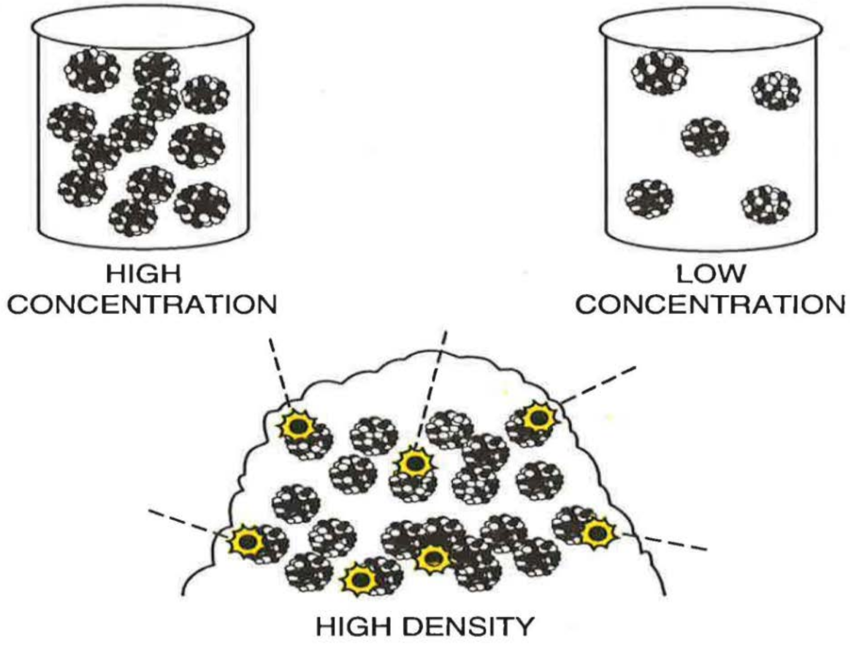
When two containers are widely separated, few neutrons escaping from one will hit the other.



When two containers are placed close to each other, neutrons escaping from each will be more likely to hit the other.

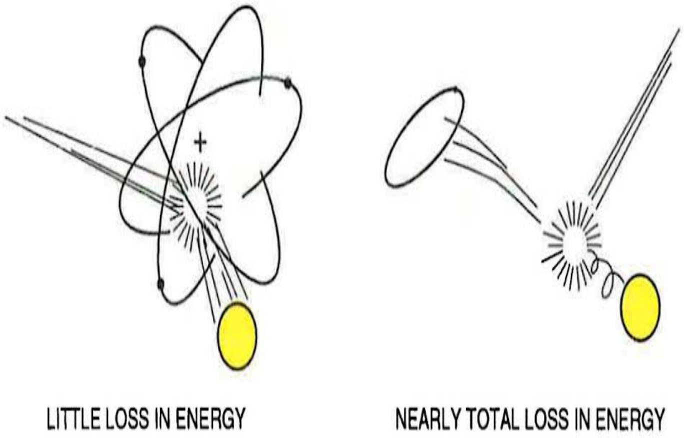
Concentration/Density

- Concentration is the number of fissionable atoms per unit volume for solutions
  - As the fissionable isotope concentration decreases, atoms spread apart, decreasing likelihood of collision with neutrons except when the diluent is a moderator.
- Density is similar to concentration for dry metals or compounds



Moderation

- Moderation is the ability of a material to slow down a neutron
  - Harder to cause fission with fast moving neutrons
  - If a neutron hits a nucleus of equivalent mass, it can lose almost all of its speed
  - If it hits a heavier nucleus, it will not be slowed down as much



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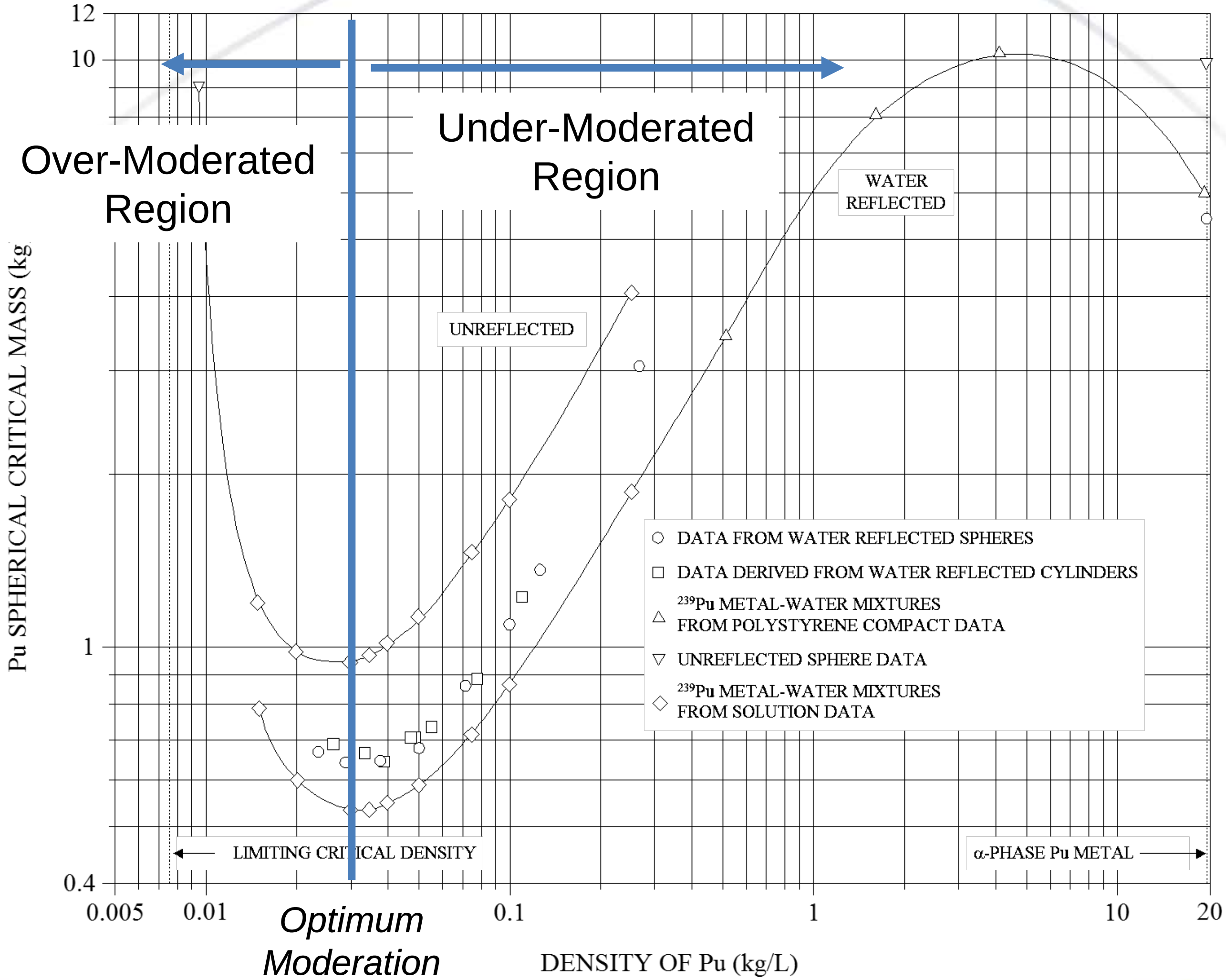
Moderation and Critical Mass



On the Pu Critical mass curve, The reduction in density, from placing the Pu in solution, greatly reduces the critical mass and reaches its peak at the *optimum moderation* point shown. Any more dilution and the critical mass increases because the Hydrogen begins to absorb more than the water moderates.

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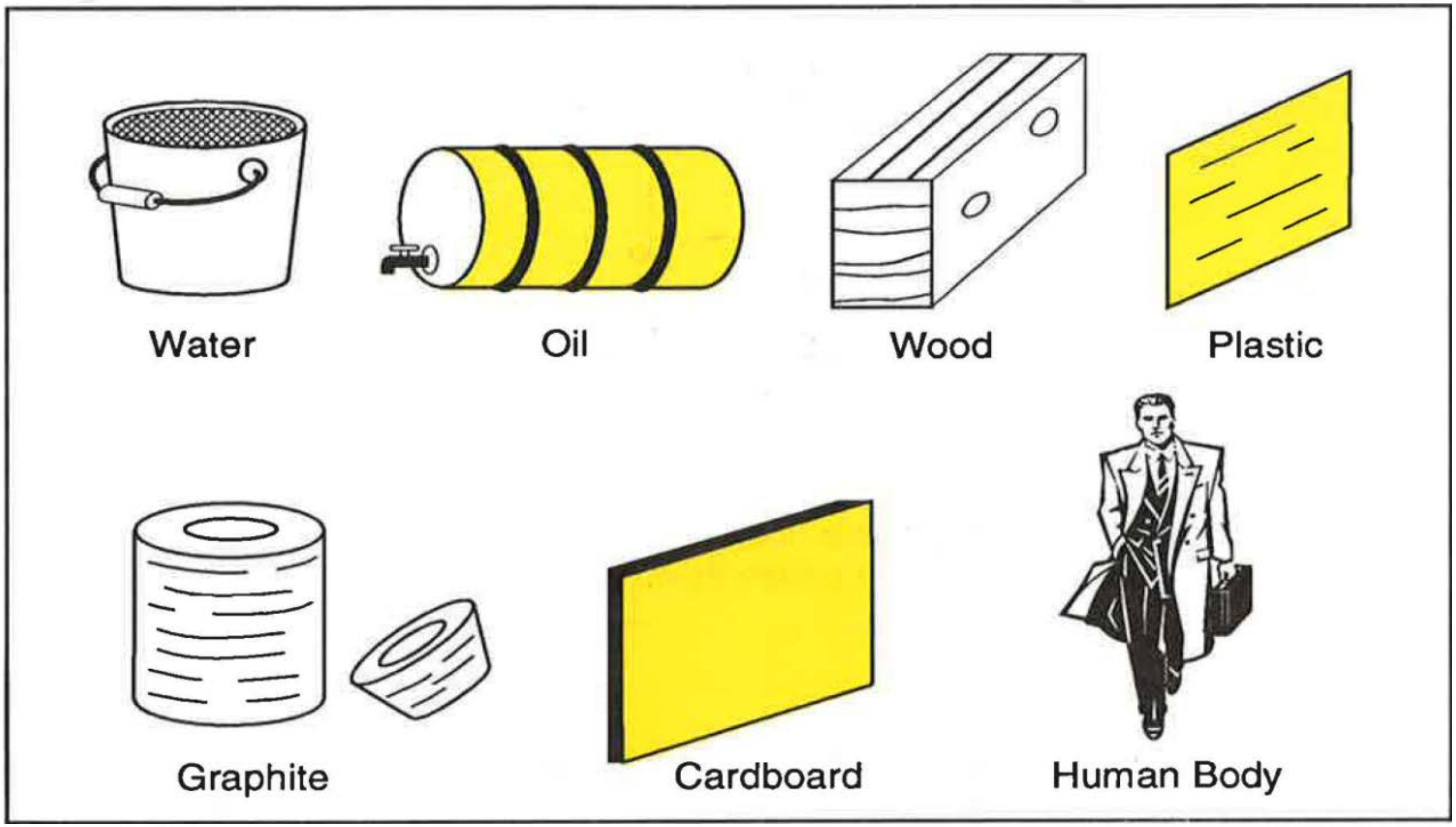
Examples of Good Moderators

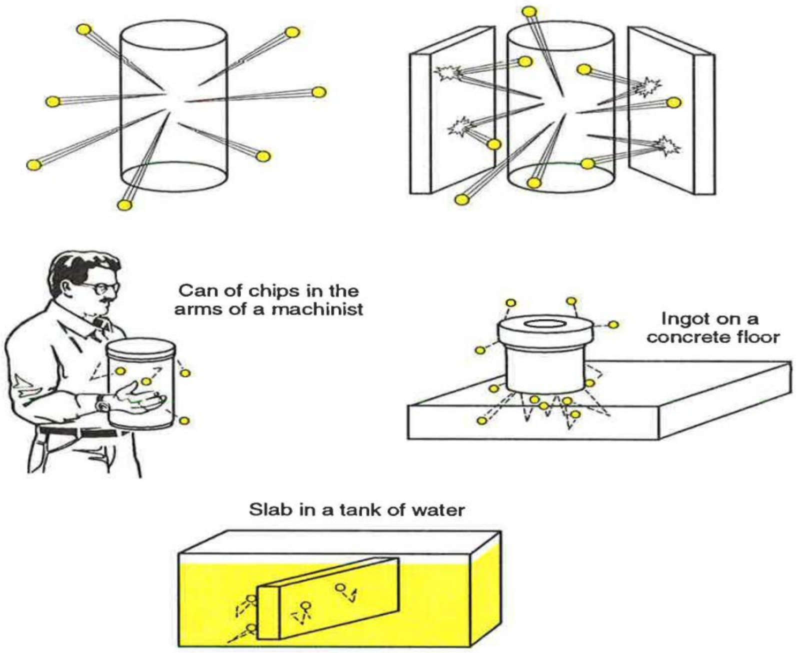


Enrichment

- Enrichment is the isotopic percentage of fissile nuclide (e.g., ^{235}U, ^{239}Pu) within the fissionable material
  - Plutonium has ^{239}Pu and ^{240}Pu
  - Uranium has ^{235}U and ^{238}U
- Fissile means the nuclide can undergo fission with thermal neutrons with a high probability
- Higher enrichment results in a smaller critical mass
- Enrichment can be controlled by limiting the isotopic percentage allowed in an operation
  - Analysts can use a bounding case (100% ^{239}Pu) in computational analyses to avoid using a control

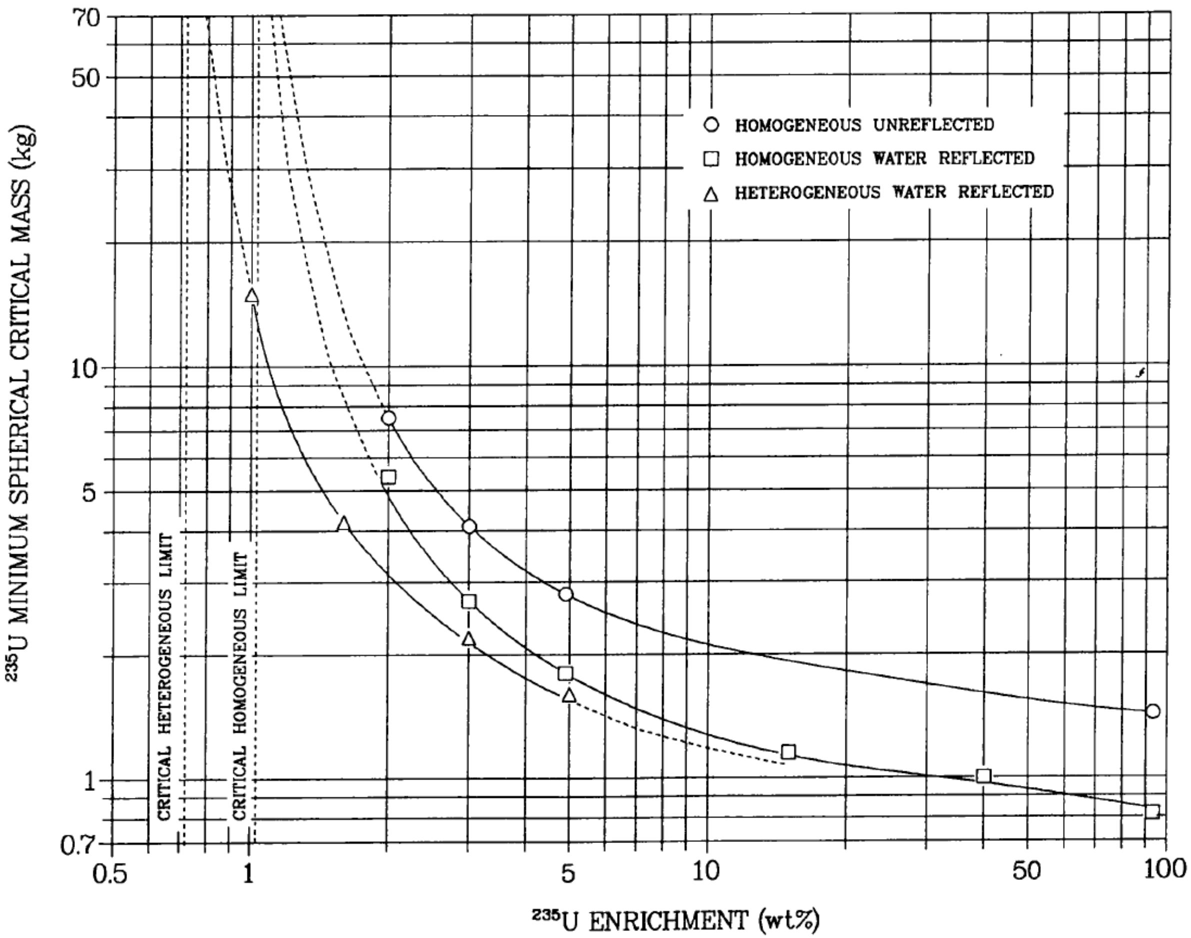
Reflection

- Reflection bounces neutrons back into the fissionable material preventing leakage as well as increasing the probability of fission
- Reflected systems have a lower critical mass than unreflected systems
- Steel, concrete, floors, columns, water, and hands are sources of reflection



Examples of Reflection

Enrichment, Critical Mass, and Reflection



With more reflection and more enrichment, the critical mass decreases. Thus, the reactivity of the system increases.

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Volume

- Volume is generally used to control solutions
  - Limits on the capacity of containers
  - Systems also have critical volumes in addition to critical mass
- Containers are designed to have favorable geometry
  - Small containers allow for neutrons to escape and requires higher concentrations/densities to reach critical

Week 3 Reading and Assignments

- Open or print the week 3 study sheet
- Read:
  - Shultis & Faw, 7.4
  - Knief, Ch. 2
- Take the weekly quiz
- Do the discussion/peer review

Due Dates:

Syllabus quiz	*Sunday, 11:59 PM*
Discussion	*Friday, 11:59 PM*
Disc. Peer Review	*Sunday, 11:59 PM*

Pages to bookmark/print:

- *Shultis & Faw:*
  - Appendix C: Fission Cross-Sections
  - Table 6.2: Nuclides which spontaneously fission

Supplemental Resources

- Nuclear Criticality Safety Engineer Training: Fission Chain Reactions
- Types of Nuclear Reactors

Week 4 – Criticality Accidents

A Brief History

Learning Objectives

After this week, you will be able to:

1. Discuss previous criticality accidents and their causal factors, including parameters involved in solution and metal critical accidents
2. Understand dosing and its effects

Radiation Basics

Radioactivity

- Amount of radiation released by a material
  - i.e. number of nuclei decaying/time
- Measured in curie (Ci) or Becquerel (Bq)
- 1 Bq = 1 decay/second

Exposure

- Amount of radiation traveling through the air
  - i.e. ionization produced in the air by radiation
- What most dosimeters and radiation monitors measure
- Measured in roentgen (R) and coulomb/kg (C/kg),

Radiation Basics

Los Alamos NATIONAL LABORATORY EST.1943

Absorbed Dose

- Radiation absorbed by an object or person
  - i.e. mean energy absorbed per unit mass
- Units in gray (1Gy = 1 J/kg) or radiation absorbed dose (1 rad = 0.01 Gy)

Dose Equivalent

- Combines absorbed dose with medical effects of the particular type of radiation and what part of the body was dosed
- Usually higher than rad
- Units in roentgen equivalent man (rem) and Sievert (Sv)

Some perspective

For acute exposure,

- *1-10 rem is relatively safe*
- *50-200 may cause illness (loss of white blood cells, nausea, vomiting, headache), increased risk of cancer, but recoverable*
- *200-1000 rem may cause death, serious illness*

DOE Annual Radiation Dose Limit Standards

Personnel Category	Section of 10 C.F.R. 835	Type of Exposure	Acronym	Annual Limit
General employees	835.202	Total effective dose.	TED	5 rems
		The sum of the effective dose to the whole body for external exposures and the committed equivalent dose to the maximally exposed organ or tissue other than the skin or the lens of the eye. (Total Organ Dose)	ED+CEqD (TOD)	50 rems
		Equivalent Dose to the Lens of the Eye.	EqD-Eye	15 rems
		The sum of the equivalent dose to the skin or to any extremity for external exposures and the committed equivalent dose to the skin or to any extremity.	EqD-SkWB + CEqD-SK and EqD to the maximally exposed extremity + CEqD-SK	50 rems
Declared pregnant workers*	835.206	Total effective dose.	TED	0.5 rem per gestation period
Minors	835.207	Total effective dose.	TED	0.1 rem
Members of the public in a controlled area	835.208	Total effective dose.	TED	0.1 rem

Table retrieved from http://www.hss.doe.gov/SESA/Analysis/rems/

New Vocabulary

- Raffinate – refers to the solvent stream that the solute has been removed from
- Raschig rings – small pieces of tube used in large numbers in packed bed columns, borosilicate rings can be used as neutron absorbers. More on this next week.
- α-phase plutonium metal- the form that Pu metal takes at room temperature when unalloyed. Its mechanical properties are similar to cast iron.

Critical Assemblies/Reactor Experiments

- >50,000 experiments
  - Designed to determine critical point
- 38 accidents
  - Severe damage to the system
  - Severe over exposures to humans
  - Physically unpredicted or equipment malfunction
- 12 deaths

Process Facility Accidents

- 10's of millions of operations since 1943
  - Designed with largest practical safety margins
- 22 accidents
  - 21 involving solution/slurry
    - 4 involving chemistry "gone bad"
  - 1 involving metal ingots
  - 0 involving powders
  - 0 in transportation
  - 0 in storage

LA-13638: A Review of Criticality Accidents

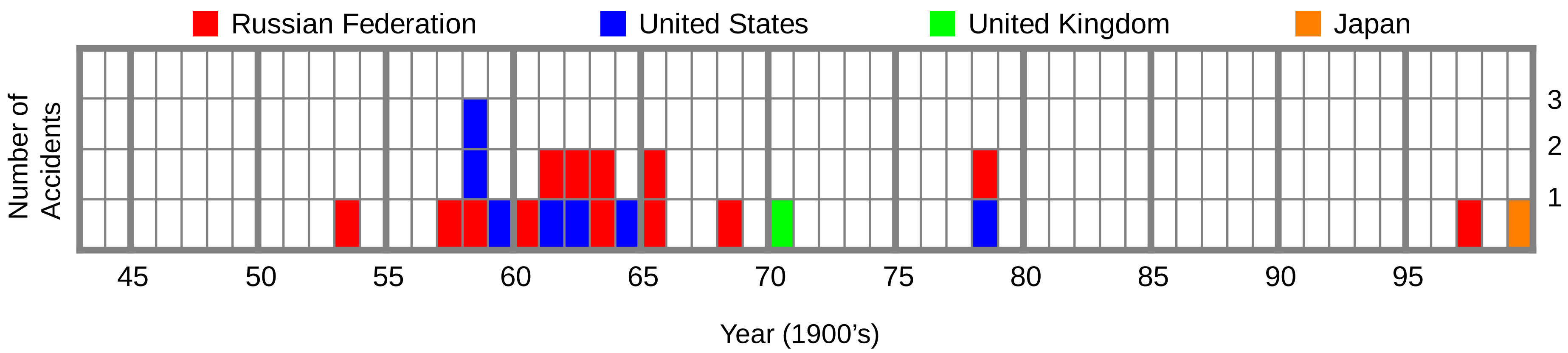
- Chronological presentation of accidents
  - Overview
  - Summary description of each accident
    - References to more in depth documents when available
  - Physical and neutronic characteristics section
  - Observations and Lessons Learned

Criticality Process Accidents by Country

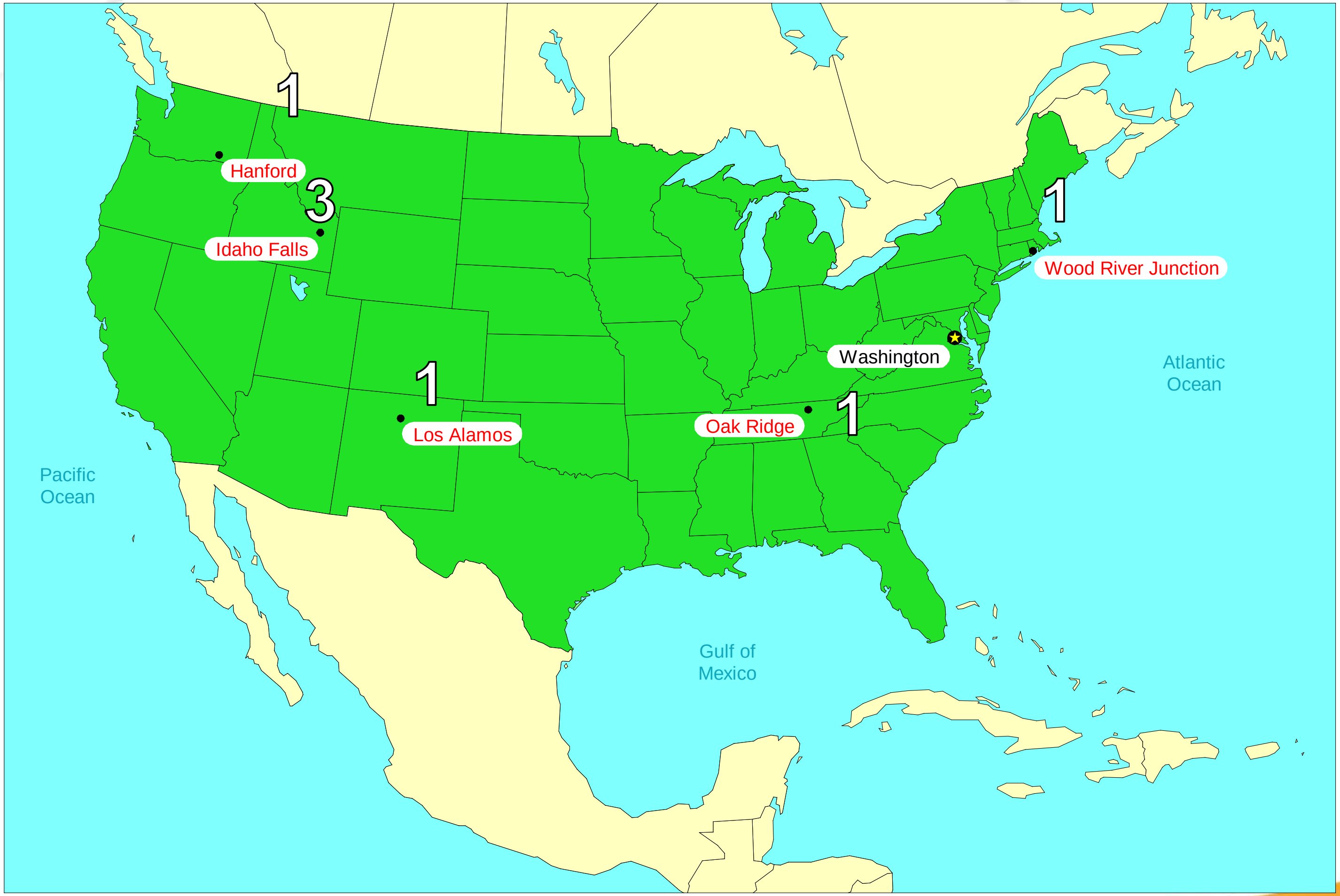
- 7 United States
  - 6 @ government facilities
  - 1 @ commercial facility, UNFR Plant
- 1 United Kingdom
- 1 Japan
- 13 in the Former Soviet Union

Parallels in History

- ~2 per year for about 10 years
- ~1 per 10 years after 1970

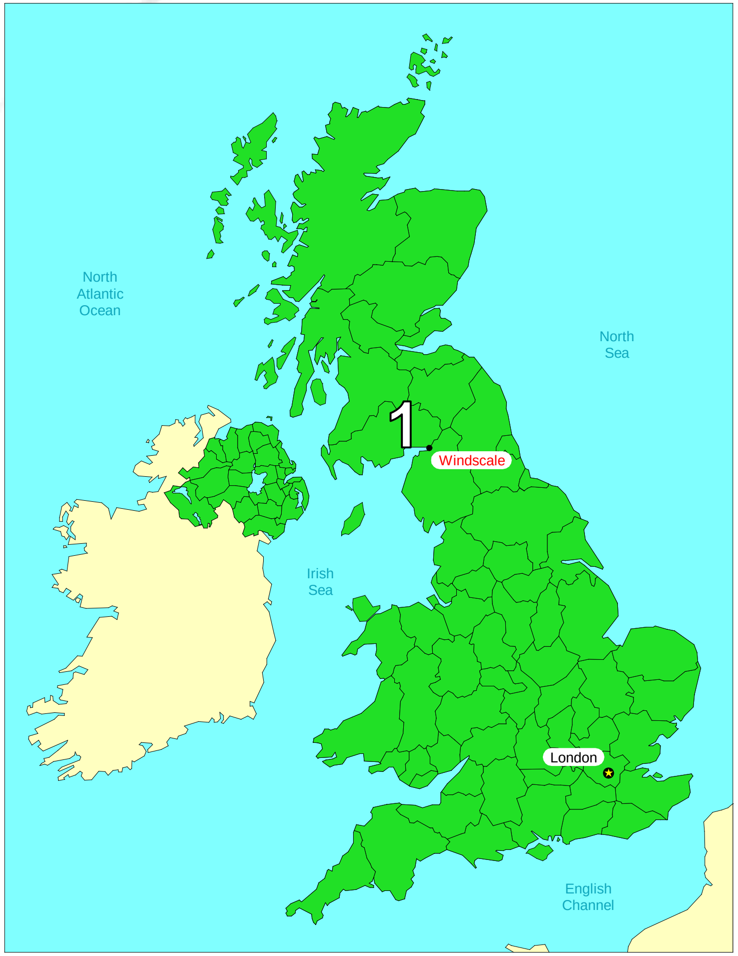


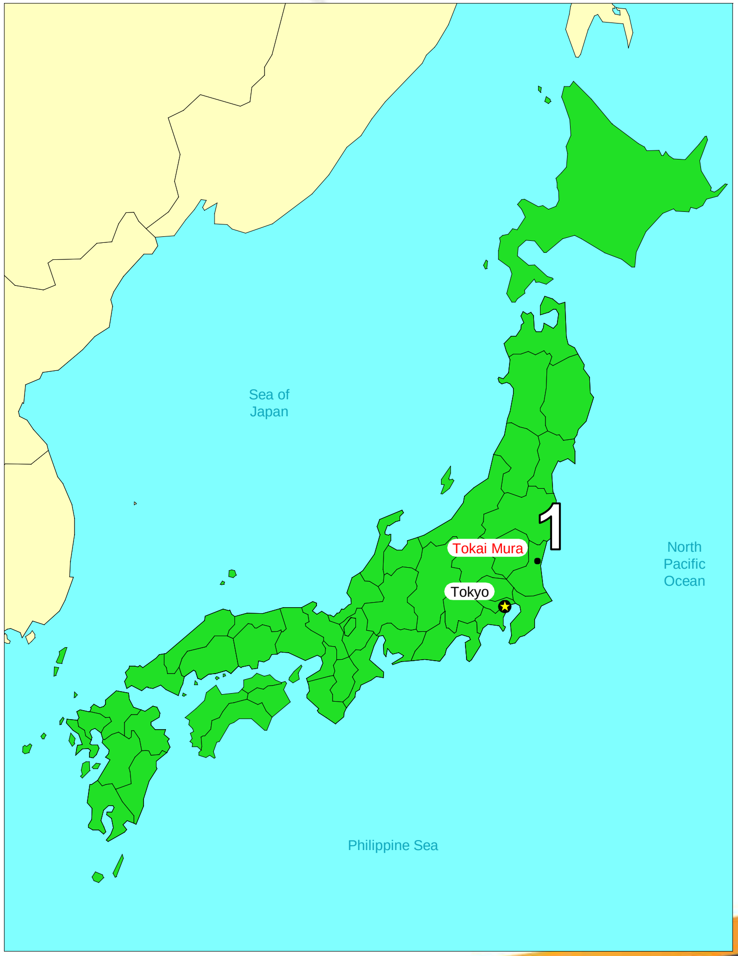
Process Accidents that Occurred in the United States



UNCLASSIFIED

Process Accidents in the UK and Japan





UNCLASSIFIED

Process Accidents in Russia

UNCLASSIFIED

Process Facility Accident Consequences

- 9 deaths
- 3 personnel required limb amputations
- Negligible environmental contamination
- No physical damage to equipment or facilities
- Measured public exposures
  - 1999 Japan accident only
  - Not health threatening

Process Accident Lessons

- General Issues
  - No single failure accidents
  - No accidents attributed to hardware failure
  - No accidents attributed to faulty calculations
  - Human factors dominated all accidents
    - Communications
    - Understanding
    - Procedural violations

Process Accident Lessons

- Management Issues
  - Avoid unfavorable geometry equipment
  - Avoid cumbersome procedures
    - Make the right job method easy
  - Important instructions must be in writing
  - Regularly observe operations
  - Evaluate operators understanding
    - Consequences of violating
      - Procedures
      - Limits

Process Accident Lessons

- Operator Issues
  - Understanding of and willingness to follow
    - Written procedures
    - Controls
    - Postings
    - Stop work policy

When you read about these accidents, consider:

- What was the process? Was it routine, abnormal conditions, etc?
- What was the assumption or thought process behind what went wrong?
- What operational errors occurred?
- What parts of MAGICMERV were involved in the excursion?
- What did the facility do to prevent the accident from happening again?

Week 4 Reading and Assignments

- Open or print the week 4 study sheet
- Read:
  – Knief, Ch. 3
  – LA-13638, selected readings
- Take the weekly quiz
- Do the discussion/peer review

Due Dates:

Syllabus quiz	*Sunday, 11:59 PM*
Discussion	*Friday, 11:59 PM*
Disc. Peer Review	*Sunday, 11:59 PM*

Pages to bookmark/print:

Reference Materials

NRC: Measuring Radiation

LA-13638 – Check under Files > Supplementary Reading

Tokai-Mura: The Forgotten Criticality (Warning! Graphic content of the effects of high radiation dose)

Study Sheets

1. Read Section 1.1 in Shultis & Faw. Fill in the blanks and answer the questions below as you progress through the reading.

   What is the surface area of a 1 m^3 barn in barns?

   How many joules are in an electron volt?

   The atomic mass of ^{12}C is ____ amu, or ________________ kg.

2. If you have the 2nd edition of Shultis & Faw, skip over Sections 1.2.1, 1.2.2, then read the rest of chapter 1. If not, read the entire section and answer the questions below:

   $^{235}_{92}U$ has ____ protons, ____ neutrons, and a mass number of ____. The number ____ does not have to be written next to U because all Uranium atoms have the same atomic mass.

   What is an isotope?

   A nuclide refers to a particular atom or nucleus with a specific neutron number ____ and atomic (_________) number ____. If nuclides are radioactive, they are termed ____________.

   Avogadro's constant $N_a \approx 6.022 \times 10^{23}$ equals the number of atoms in ______________________.

3. Read Chapter 4,

   According to Einstein's Special Theory of Relativity, the change in mass is equal to

   _________________________.

   If mass is gained in a nuclear reaction, the reaction is _____________; if mass is removed, it is

   _____________.

   Could we use the theory of relativity for chemical or mechanical reaction energetics? Why or why not?

   What is nuclear binding energy?

Using atomic mass tables (Appendix B.1 or online) Determine the binding energy (in MeV) per nucleon for the nuclides:

$^{208}_{82}Pb$

$^{239}_{94}Pu$

$^{16}_{8}O$

How can you write the equation for nucleon separation energy in terms of nuclear binding energies?

What element can be used to model an alpha particle?

Note the notation of the nuclear reactions. The first term in parentheses is the input, where the second term is the output. What would a (p, αn) reaction look like for protons interacting with ^{238}U?

What does the Q-Value quantify in a nuclear reaction?

Q = (__________________________)c^2 – (_____________________________)c^2

Set up example 4.3, 4.4, and 4.5 and go through the steps to make sure you understand them.

4. Look over Chapter 5, sections 5.1-5.4. You may want to bookmark or print out Table 5.1 for later reference. This chapter will give further information on nuclear reactions and reaction types in the case that they come up again. Equations, symbols, and terms that you should become familiar with are:

    Conservation of charge:

    Conservation of nucleon population:

    Radioactive decay diagram:

    Gamma decay:

    Alpha decay:

    Beta-particle decay:

    Positron decay:

    Neutrino and antineutrino:

    Electron capture:

    Neutron decay:

    Proton decay:

5. Read 5.5, then answer the questions:

    What are the two ways of quantifying radioactivity?

The isotope ^{132}I decays by beta-particle decay to ^{132}Xe with a half-life of 2.3 hours. How long will it take for 7/8 of the original number of ^{132}I nuclides to decay?

What are the SI units for activity? What is the conversion to Curies?

To solve for the activity (decay rate), you must know or find the ____________ and ____________.

6. Read Section 6.1: Types of Binary Reactions

Write down the definitions for the reaction nomenclature in your own words:

Transfer Reactions:

Scattering Reactions:

Knockout Reactions:

Capture Reactions:

Nuclear Photoeffect:

7. Read section 7.4: Neutron Interactions

All cross-section data are _________________ in nature, with little guidance available for interpolation between ___________________ or __________________.

Nuclides are usually divided into three broad categories: ___________, with mass number < 25; ______________, and ____________, with mass number >150.

Fissile isotopes are those which can undergo fission upon the absorption of a __________. Important fissile isotopes are ____________________.

1. Read Knief, Chapter 2: Fundamentals

   Nuclear criticality safety has been defined as
   "____."

   What three major components does Nuclear criticality safety have, according to Alcorn?

   Criticality safety aims to prevent what kinds of accidents?

   Write down the 4-factor formula and what each symbol means:

   What is the difference between k_∞ and k? What do you have to multiply to get k from k_∞?

   Using the 4-factor formula and the last question, derive the 6-factor formula and label each symbol:

   How are geometrical and material buckling used to estimate criticality?

   In a critical system, production rate = _____________________ + _____________________

   In typical power reactors, what is used to control the production rate of the nuclear source?

   Complete the MAGICMERV acronym below and fill in "increases" or "decreases" for the blanks

M-	Increasing fissile mass in the system generally _____________ k_{eff}.
A-	Increasing absorption or poisoning ____________ k_{eff}.
G-	____________ in surface area or ____________in density enhances leakage, which __________ k_{eff}.
I-	The closer two fissile materials are placed near each other, the chance of neutrons interacting ______________, which increases k_{eff}.
C-	An increase in density ____________ critical mass, so expanding a material would __________ k_{eff}.

M- Increasing the amount of moderator in an under-moderated fissile material system ___________ the probability of fissions, which ___________ k_{eff}.

E- With higher enrichment, critical mass ___________

R- Reflection in a system ____________ critical mass because it prevents neutron leakage

V- As the volume ____________, the concentration or density needed to reach critical decreases

Define “geometrically favorable” and explain its importance in criticality safety.

Moderators work by ___________ the energy or speed of the neutron. This works with lighter nuclei more than heavy nuclei because the neutrons would ___________ scatter from heavy nuclei.

Is a fissile material considered more stable when its critical mass is lower or higher?

Look at Figure 2-2 and 2-3. Why are there multiple points of the same size or critical mass at different concentrations or radii? What variables in MAGICMERV are causing the overlap?

Why does plutonium metal have a higher critical mass than plutonium in water?

In a reactor system, what are the major feedback mechanisms that reduce the neutron multiplication? How do pulse reactors use this to their advantage?

In a typical nuclear fuel cycle (Figure 2-5), which steps require a nuclear criticality safety program?

For this reading, you may want to find the corresponding section of LA-13638, “A Review of Criticality Accidents,” for each accident listed in the chapter. The literature is a great reference and covers all criticality accidents that have happened before the year 2000. Luckily, no criticality accidents that we know of have happened since 1999 (And we’d like to keep it that way!), so LA-13638 is up to date when it comes to criticality accidents.

Knief, Chapter 3

1. Accident Experience:

   Why would stacking tungsten carbide bricks around a plutonium sphere cause a criticality accident?

   What could the researcher in the first accident have done to lower his exposure from the event?

   Why was the guard that was standing ~12 ft away not affected?

   ~800 rad took the researcher’s life in ______ days

   In the second accident, what could have prevented the criticality event?

2. Y-12 Plant

   The leak in the piping did not initially cause a criticality until emptied into the drum because the storage tanks had ______________ geometry.

   ________ fissions were released in total, 100 times more than the accident in 1945

   The critical solution was brought back to subcritical levels by _______________________

   Were there fatalities? Why or why not?

   What changes were made to prevent an accident from happening again?

3. Los Alamos Scientific Laboratory (1958)

   What was the change in procedures that could have prevented the accident?

   What was the mass concentration of plutonium in the organic layer?

   What caused the solution to go critical? What made it return to subcritical?

   What was done to prevent further accidents?

   Why does borosilicate glass work as a neutron absorber?

4. Idaho Chemical Processing Plant – First Excursion

   What was the change in procedures that could have prevented the accident?

   What was the mass concentration of uranium in the solution?

   What caused the solution to go critical? What made it return to subcritical?

   Were there fatalities? Why or why not?

   What was done to prevent further accidents?

5. Idaho Chemical Processing Plant – Second Excursion

   What was the mass concentration of uranium in the solution?

   What caused the solution to go critical? What made it return to subcritical?

   Were there any significant doses to personnel? Why or why not?

   What was done to prevent further accidents?

6. Recuplex Plant

   What caused the solution to go critical? What made it return to subcritical?

   Were there any significant doses to personnel? Why or why not?

   What was done to prevent further accidents?

7. Wood River Junction Plant

   What was the change in procedures that could have prevented the accident?

   What caused the solution to go critical? What made it return to subcritical?

   Were there any significant doses to personnel? Why or why not?

What was done to prevent further accidents?

8. Windscale Works

   What caused the solution to go critical? What made it return to subcritical?

   Were there any significant doses to personnel? Why or why not?

   What was done to prevent further accidents?

9. Idaho Chemical Processing Plant – Third Excursion

   What caused the solution to go critical? What made it return to subcritical?

   Were there any significant doses to personnel? Why or why not?

   What was done to prevent further accidents?

10. General Observations

    The concentration of accidents is partially attributed to ____________________ of highly enriched uranium and plutonium without growth in the facilities. Plants originally designed for moderate capacity and minimal criticality safety guidance were__________________________.

    That the excursions have occurred in ____ is not unexpected.

    Also take note of Table 3-III. This will come in handy later when trying to identify likely upsets in a process.

LA-13638: A Review of Criticality Accidents

If you hadn't noticed, the accidents listed in Knief are a bit dated, and only cover what happened in the US and in the United Kingdom. This book accounts for all criticality accidents that are known to the US since 2000, including more recent accidents like the Tokai Mura accident that occurred in Japan in 1999. We will only go through a few of the accidents listed in this review, but feel free to read more than what is assigned!

11. Siberian Chemical Combine, 13 December 1978 (p.47)

    The containers in the process were lined with ____________ as a neutron absorber.

    It was assumed that the operating personnel, ______________________________, would not make gross errors in loading the containers.

12. JCO Fuel Fabrication Plant. 30 September 1999 (p. 53)
    [Also known as the Tokai-Mura accident]

    This was the first process criticality accident in which measurable exposures occurred to ____.

    There were 2 process deviations that led to the criticality accident:

    a) The dissolution step was to be conducted in ___________________ instead of the vessel indicated to save time.
    b) The transfer of the nitrate solution into the ____________________________ precipitation vessel, instead of the prescribed, favorable geometry columns.

    To terminate the excursion, small teams of operators were sent in to ____________________________________.

    To assure subcriticality, __________________ was added to the precipitation vessel through a long rubber hose.

    Assume GyEq is equal to Sieverts. Converting Sv to rem, what was the effective dose in the workers?

Weekly Discussion Topics

Discussions for weeks 1-4 of the Nuclear Criticality Safety Course

Week 1 Discussion: Introductions

Hello everyone!

For this first discussion assignment, please introduce yourself with the following information:

- Name
- Where you're from
- Where you are in the CHME program (Sophomore, Junior, Senior)
- What made you want to take this class
- A fun fact about yourself
- Any hobbies you might have

Fun facts can include, but are not limited to:

- Speaking six languages
- Owning a pet snake
- Being able to write backwards
- Playing golf
- Enjoying good books
- Enjoying bad books
- Having an imaginary friend
- Eating as a sport
- Uncontrollable giggling when puppies are mentioned

Also, please watch the following YouTube video on Nuclear Criticality Safety https://www.youtube.com/watch?v=H1ckdTlgvlU (Links to an external site.)Links to an external site and give one comment about what you thought was interesting, funny, or hard to understand.

For the peer review, give a short, 2-3 sentence response to your peer's comments and anything you have in common with them. Try to read everyone's discussion entry, not just the ones assigned to you!

Week 2 Discussion: Fission and binding energy

When considering nuclear fission, usually only the heaviest radioactive nuclear atoms are easily fissioned. In a fission reaction, the atom is split into two lighter nuclei, releasing energy and nucleons.

Look at the attached figure from Shultis and Faw that shows the binding energy curve for different mass numbers and discuss why only the heaviest atoms are easily fissioned. Cite any sources that you use to back up your answer.

Week 3 - Neutron Absorbers

Now that you've learned the fundamentals of criticality safety, let's focus on one of the components of MAGICMERV: Absorbers. Neutron absorbers are not usually used as a direct control due to their maintenance requirements, but are used as defense in depth (extra safety) and are vital for controlling nuclear reactors. Look up one of the following absorbers, explain its characteristics, absorption cross-section, availability, and why it works as a good neutron absorber:

Cadmium

Boron

Chlorine

Gadolinium

Hydrogen

Week 4 - Criticality Accidents

As you may have noticed, many of the accidents covered in LA-13638 were not covered in the text. For this week's discussion, choose an accident that we did not cover, summarize the accident in 1-2 paragraphs, then identify the contributing factors and lessons learned from the accident.

Have you noticed any common contributing factors to the accidents? Is there anything that seems to cause issues?

CHME 491 Course Syllabus

CHME 491. Special Topics – Introduction to Nuclear Criticality Safety

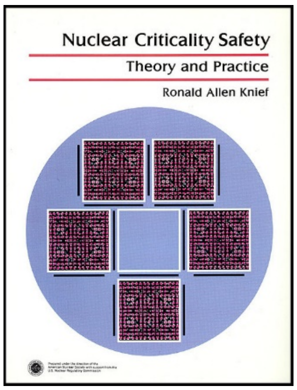
Instructors

Alicia Salazar-Crockett aliciasa@lanl.gov

Andrew Wysong wysong@lanl.gov

TA – Elijah Wade eliwade@nmsu.edu

Textbook



Required: Nuclear Criticality Safety Theory and Practice, Ronald Allen Knief, American Nuclear Society Publishing (2000)

Get it at http://www.ans.org/store/item-300020/ for $65.00 (cheapest we found)

Optional: If you already own the CHME 471 textbook**, Fundamentals of Nuclear Science and Engineering**, J. Kenneth Shultis, Richard E. Faw, Second Edition (2008), some helpful reading will be assigned out of this book for the nuclear physics portion of the class. If you do not own this book, a pdf with the selected readings will be provided. You do not have to purchase this book.

Supplemental materials – can be found on Canvas in 'Supplemental Reading' folder

- LA-14098 – Modern Fission Theory for Criticality by J. Eric Lynn
- LA-14244-M – Hand Calculation Methods for Criticality Safety – A Primer by Douglas G. Bowen and Robert D. Busch
- LA-13638 – A Review of Criticality Accidents (2000 Revision) by Thomas P. McLaughlin, Shean P. Monahan, and Norman L. Pruvost

Specific course information

a. Catalog description: Introduction to the concepts and practice of nuclear criticality safety. Includes an introduction to nuclear physics, overview of criticality safety accidents, Orders/Standards applicable to criticality safety. Introduction to hand calculations and Monte Carlo methods used in criticality safety analysis. Application of skills learned in preparation of criticality safety evaluation.
b. Prerequisites: none co-requisites: none
c. Required, elective, or selected elective (as per Table 5-1): elective

Learning objectives

The student will be able to…

- Demonstrate a basic understanding of nuclear fission and fusion
- Explain and define criticality safety factors for operations

- Discuss previous criticality accidents and their causal factors, including parameters involved in solution and metal critical accidents.
- Identify and discuss the application of several common hand calculation methods
- Describe the importance of validation of computer codes and how it is accomplished.
- Describe the methodology supporting Monte Carlo codes and deterministic codes.
- Discuss ANSI/ANS criticality safety regulations
- Describe DOE regulations and practices in the NCS field
- Complete a Criticality Safety Evaluation

Criterion 3 Student Outcomes specifically addressed by this course are found in a mapping of outcomes against all CHME courses in the curriculum.

Grading Policy

95-100%	A+
90-94%	A
85-89%	B+
80-84%	B
75-79%	C+
70-74%	C
60-69%	D
<60%	F

Grade weight

Quizzes	15%
Video Chat Attendance	10%
Discussions	25%
Midterm	25%
Final Project	25%

Course Structure

Course Slides

Weekly coursework slides will be posted every Monday. These pdfs will list your assigned readings, any further assignments, the discussion briefing, and any supplementary materials that you may want to look at to solidify your understanding of the material. These slides should be the first thing you look at every week.

Assigned readings and study sheets

Assigned readings will be listed in the week's powerpoint found on the canvas drive. For each weekly reading assignment, an accompanying study sheet can be found in the 'Study Sheets' folder on Canvas. These are for you to fill out as you go through the reading, which act as study guides that also improve your abilities to retain what you read. These do not count as class credit, but will be extremely useful for the midterm and quizzes.

Discussions

Discussions will be a large part of this class. Every week, a new topic or case will be presented where you will have to write a few paragraphs or do some calculations to answer the question. These responses should use at least one outside source and should have an informal citation including the document name, book and author, or website.

Peer Reviews

To receive full credit for discussions, you will also have to review the discussion responses of two of your peers. These are randomly assigned, and require meaningful 1-2 paragraph responses/reflections. You should be reviewing the content to see if you have any suggestions, comments, or disagreements. These should provide useful feedback and constructive criticism for the peer you are reviewing, not insults or unnecessary arguments.

Quizzes

The quizzes are designed to help you reflect on your reading assignments. Many of the questions will be modified versions of the study sheets, so completing the study sheets before taking the quiz will be essential. The quiz will be timed, and questions will be pulled randomly from a pool. You will be able to take the quizzes over again and see what you got wrong.

Video chats

This course has bi-weekly video chats where you will get to share questions, ideas, and speak with us. Since this is the only time that we get to meet, attendance will be counted for 10% of your grade. Scheduling for the video chats will be decided during the first week of the course.

Policies

Due dates

Quizzes, discussion posts, and peer reviews are due each week at 11:59 PM every Sunday, Friday, and Sunday, respectively, unless stated otherwise. After the due dates, assignments will close and students that missed the deadline will be given zeros for that assignment.

Academic Misconduct

The CHME Department expects all constituency to abide by the AICHE and NSPE Codes of Ethics.

The CHME Department follows a ZERO tolerance policy regarding academic misconduct. Every such incident will be reported to the Associate Dean of Academics in the College of Engineering with a request for the maximum allowable penalty for unethical actions.

Any student who is found guilty of academic misconduct as cited in the NMSU Student Handbook under Section III.B will be assigned of a grade of "F" for the course. The Student Code of Conduct defines academic misconduct, non-academic misconduct and the consequences or penalties for each.

CHME students accept and agree to fulfill their responsibility to report (in writing) to the supervising professor with copy to the department head should they observe any solicitation for assistance or action that can be regarded as cheating within 24 hours of the completion of an assessment activity.

Where they may differ, the Regulations & Policies Section of the current NMSU Academic Catalog takes precedence over the Student Handbook.